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HIGH POWER TRIGGERED SPARK GAPS

BY

ALVIN ERNEST GILLOGLY

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HIGH POWER TRIGGERED SPARK GAPS

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A. E. Gillogly

HIGH POWER TRIGGERED SPARK GAPS

by

Alvin Ernest Gillogly,
Lieutenant Commander, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
MASTER OF SCIENCE
in
ENGINEERING ELECTRONICS

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Annapolis, Maryland
1950

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PREFACE

A portion of the material herein presented was obtained while on duty at the Westinghouse Electric Corporation, Baltimore, during the period 3 January - 17 March, 1950. Work was conducted on an experimental triggered spark gap modulator under the guidance, and with the assistance of the engineers in the Radar Section, Government Engineering Group, Electronics and Xray Division. The author wishes particularly to acknowledge the helpful advice and assistance rendered him by Mr. D. R. Trashjian, the Section Engineer, and Messrs. R. N. Riley and H. L. Jackson.

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LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

C_{st}---- storage capacity of PFN

δ ---- pulse width in microseconds

E------ power supply voltage

I_L----- d-c current in the load

KV----- kilovolts

L------ inductance

L_{ch}---- inductance of the charging reactor

Ω ---- ohms

ω ---- angular frequency

ma----- milliamperes

μ ----- micro-

p.p.s.- pulses per second

PFN---- pulse forming network

PRF---- pulse repetition frequency

R------ resistance

R_o----- characteristic resistance of PFN

R_L----- load resistance

I

INTRODUCTION

1. Brief history of development

The attempt to increase radar range by the "brute force" method of transmitting morepowerful pulses has again created a switching problem. At peak powers of 500 kilowatts and below the hydrogen thyratron has proven to be a cheap, compact, and reliable switch. In the megawatt region of peak pulse powers the hydrogen thyratron is, at this time, very expensive and unreliable. The possibility of using triggered spark gaps in high power radar modulators is therefore being investigated.

Early spark gap investigations covered such possibilities as fixed two-and three-electrode gaps operating in air with forced circulation of the air in order to aid deionization, veatrons (vacuum arc devices), and ignitrons. The trigatron an enclosed three-electrode gap was found to give satisfactory service for low power applications in which long life was not required.

Recently the Microwave Laboratory at the University of California has been investigating the use of open-air triggered spark gaps at very high powers and low repetition rates. This latter work has been mainly at peak pulse powers of 200-400 megawatts, at pulse repetition rates of 60 cycles per second and below.

The work at Westinghouse was undertaken to investigate the possibility of using open-air triggered spark gaps to switch peak powers of around 6-8 megawatts at a pulse repetition rate of 1200 cycles per second. An experimental modulator was constructed in which peak pulse powers of 8 megawatts were switched at 1200 cycles per second. This is believed to be the first attempt to use open-air triggered spark gap switches at both high power and high repetition rates. The air blast required is a major disadvantage of this type switch. Up to 200 cubic feet of air per minute was required.

2. The nature of the spark discharge.

When the voltage between two electrodes is raised to, or above, the static-breakdown point, a spark will occur. (In figure 1 this gap threshold voltage, as determined independently by Schumann and Fletcher (1) is plotted vs. gap width). This spark is caused by the breakdown of the gas in the region between the electrodes, and is a result of the ionization of the gas molecules by the accelerated free electrons in the vicinity. This acceleration is imparted to the electrons present by the electric field existing between the terminals, and is directly proportional to the potential difference across the gap. The higher the applied voltage, or the greater the number of free electrons present, the shorter the elapsed time between application of the voltage and initiation of the discharge. For example, if the voltage

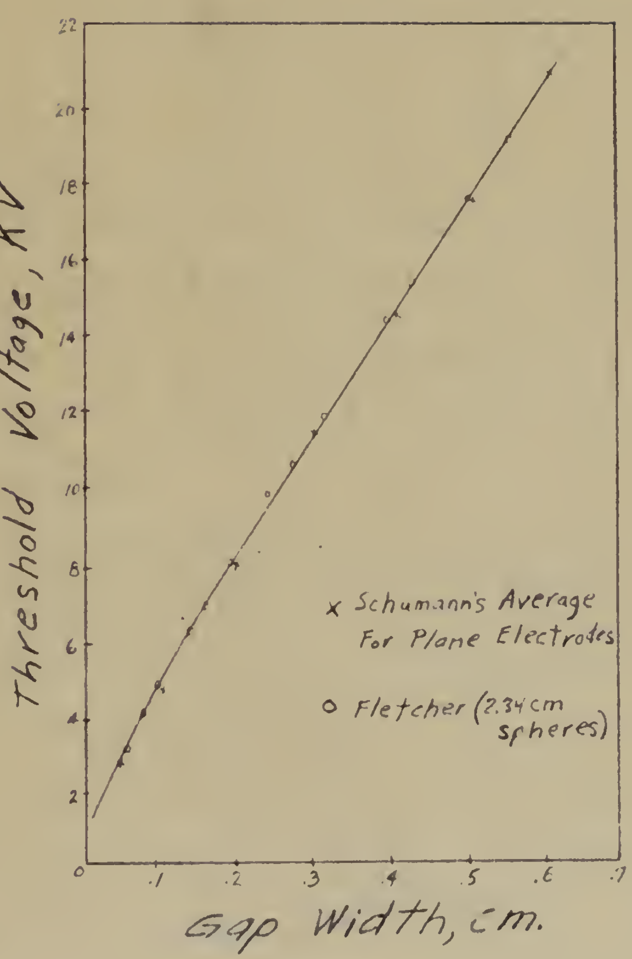
Threshold Voltage, KV
Gap Width, cm.
x Schumann's Average For Plane Electrodes
o Fletcher (2.34 cm spheres)

Fig. 1

is just equal to the static-breakdown potential, a "time lag" of several minutes may occur. If the voltage is raised to a value two or three times the minimum required, the time lag is reduced to the order of hundredths or even thousandths of a microsecond, Windred (2). After the ionization commences, a short interval, of the order of .01 microsecond, transpires before the discharge attains the properties desired for use as a switch. At the end of this very short "breakdown time", the gas between the electrodes has changed from an insulating medium to one capable of carrying quite high currents. Factors determining the characteristics of discharge are the type of gas, gas pressure, gap geometry, and the shape of the applied voltage wave.

In order to utilize the above properties of the spark, the breakdown must be controlled, and this can easily be done by heavily overvoltageing the gap. In the case of a fixed gap, a high transient peak voltage is applied to one electrode. For three electrode triggered gaps the high transient peak voltage is applied to the trigger electrode which causes the trigger gap to breakdown. This ionizes the gas molecules and the main gap breaks down a fraction of a microsecond later.

II

PREVIOUS DEVELOPMENTS

1. British triggered gaps

   a. General development

The work on the British trigatron* commenced in January 1941, Craggs (4). Although rotary gaps had been found suitable for certain applications, it was desirable for a stationary-electrode system to be produced in which the spark discharge could be controlled at accurately de-determined instants by the incidence of a regularly recurring trigger pulse. A gap of this type was developed to a satisfactory state for operation in open air by the summer of 1941.

The open air trigatron consisted essentially of three electrodes, arranged as shown in figure 2(a). It was connected in the circuit so that the undrilled electrode was negative with respect to the drilled electrode and the trigger electrode. The latter two electrodes were normally at the same potential and were connected by a high resistance. The trigger pulse was positive with respect to the surrounding electrode. About a 3 to 6 KV trigger pulse of short duration was used. The method generally used to provide these pulses employed the voltage across an inductance in the plate of a large vacuum tube that was cut-off at the repetition frequency. Typical

*Metropolitan Vickers Electrical Co., Ltd.

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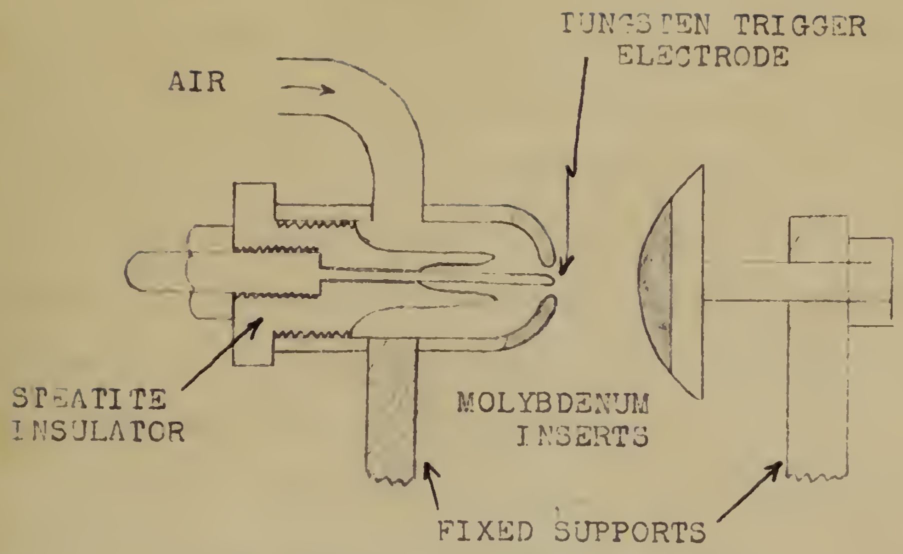
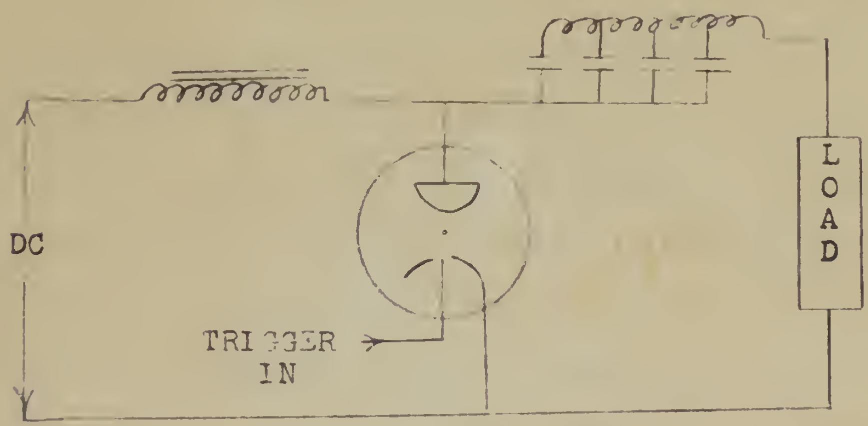


Cross Section View of Trigatron

(a)



Basic Trigatron Modulator Circuit

(b)

Fig. 2

values used were a current of 1 ampere and an inductance of 10 millihenries which produced a peak voltage of 10 KV. The peak value of the trigger voltage was reached in about 1.5 microseconds. The coupling arrangement between the trigger tube and the trigger electrode was usually a condenser shunted by a high resistance leak, of about 100,000 ohms. Another resistance of the order of 1000 ohms was found to be desirable in series with this condenser and the trigger wire to suppress oscillations occurring immediately after breakdown of the trigger gap.

Because of the need for the use of the equipment in aircraft, consideration had to be given to compactness of design and lightness of weight. It was also necessary for the apparatus to operate at high altitudes and therefore at reduced air pressures. This made it urgent for a spark-gap to be developed to operate in a sealed enclosure, and after investigation of the behaviour of the gaps in various gases and gas mixtures and with different electrode materials, a satisfactory form of sealed gap, now known as the trigatron, was developed by January, 1942. The trigatrons, which were the prototypes of the commercially-produced models, consisted of glass bulbs containing a mixture of approximately 95 per cent argon and 5 per cent oxygen at a pressure of 1 to 6 atmospheres with sparking surfaces of molybdenum and tungsten. Oxygen was used in a trigatron principally to maintain an oxide coating on the surfaces

of the electrodes and thereby to limit the rate of electrode erosion. Oxygen was also needed in these gaps to quench mestastable atoms of argon after discharge. The life of the trigatrons is around 300-500 hours. Failure is caused by a reduction in the amount of oxygen present, by combination with the molybdenum and tungsten electrodes, to a value that is insufficient to quench metastable atoms of argon after the discharge, Craggs (4). The tube then fails to deionize properly. Failure is not caused by electrode erosion, for it operates satisfactorily after being pumped and refilled.

Further discussion of enclosed triggered gaps will not be presented here, since this paper is concerned primarily with open air triggered gaps.

b. Mechanism of operation

If the breakdown voltage of the gap between the two main electrodes of the triggered spark gap in the absence of the trigger voltage is V_{max}, then the breakdown may be caused to occurr at any voltage V down to V_{min} on the application of the trigger pulse. The voltage V may be maintained indefinitely across the gap until the trigger pulse is applied.

The reduction in normal breakdown voltage is thought to be caused by the concentration of the voltage gradient in the region of the trigger electrode on the application of the trigger pulse, Craggs (4). While the magnitude of

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the trigger voltage has some effect on the amount of lowering of the breakdown voltage, the observations show that the lowering is considerably greater than that to be expected by direct addition of the trigger voltage to the voltage applied between the main electrodes. With short gap spacings, oscillographic studies show that, over at least part of the operating range, the voltage on the trigger electrode has dropped to about that of the surrounding electrode before breakdown of the main gap takes place. In this case the lowered breakdown voltage of the gap may be caused by field distortion in the gap due to space charge formation resulting from the photo-ionizing effects of the trigger spark.

A further consideration in the operation of the triggered gap is the need for irradiation of the gap, so that the presence of primary electrons to initiate the discharge is ensured at the instant the voltage pulse is applied. This irradiation is provided by corona discharge which forms around the trigger electrode. In the British trigatron the insertion of an insulating cylinder of high dielectric-constant between the wire and the surrounding anode (see figure 2a), causes the gas in the vicinity of the wire to become highly stressed and the corona discharges is thereby intensified.

While the operating range of the triggered gap when used to control single discharges lies between the voltages

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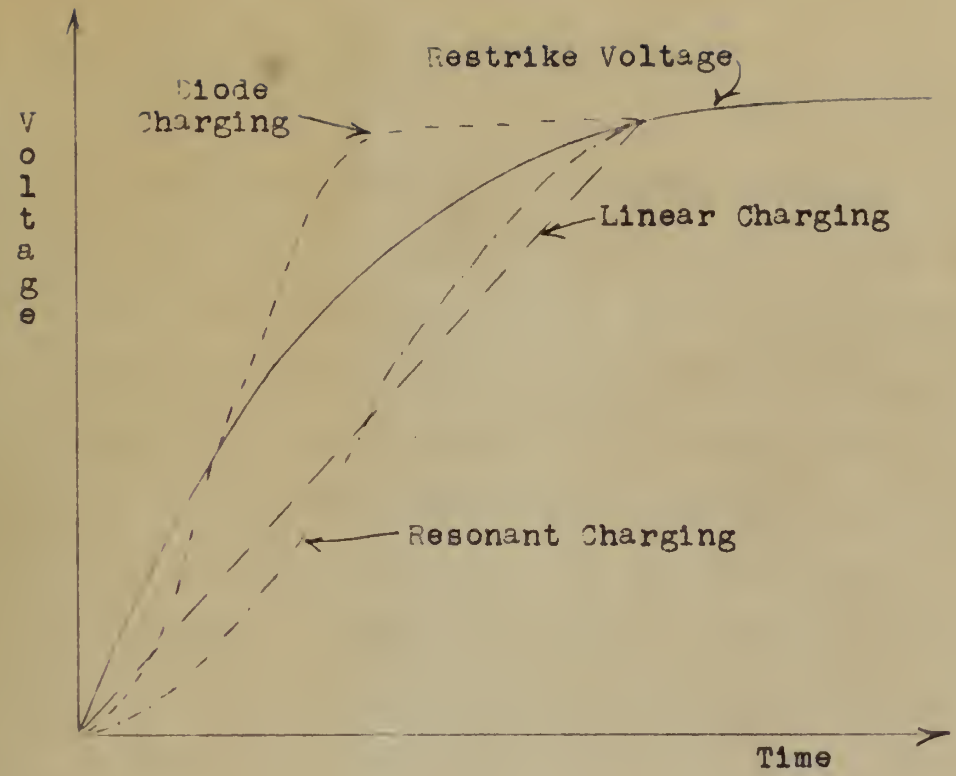
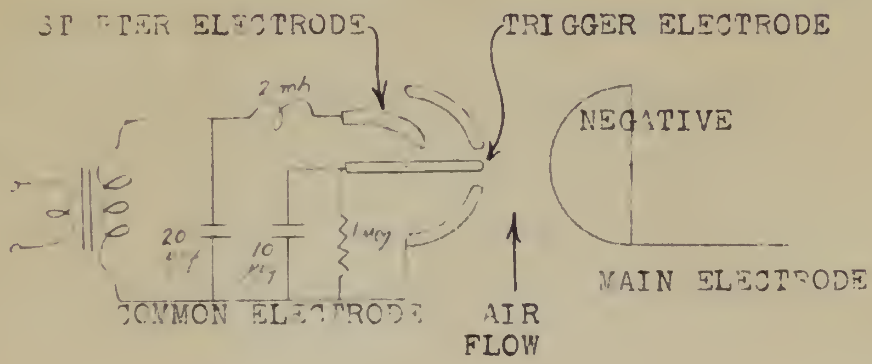
V_{max} and V_{min}, the operating range for recurrent pulses is affected both by the pulse energy and the PRF. This is because the dielectric strength of the gap has not fully recovered from the effect of one spark before the next spark occurs. For this reason the maximum operating voltage decreases with increasing PRF.

Consideration of the manner in which the dielectric strength recovers enables an explanation to be given of the improved performance of the trigatron which was observed when linear charging was used in preference to resonant charging. This may be seen by reference to figure 3, where a comparison is made between the linear charging curve, the resonant charging curve and the re-striking curve. (The latter was determined essentially by observing the lowest steady d.c. voltage at which spark breakdown occurs in the main gap when the trigger voltage is continuously applied, Craggs (4).) It is essential that the charging curve should fall beneath the re-striking curve, or else breakdown of the gap will occur before the voltage reaches the required crest value. This corresponds to what is known as pre-firing of the gap. Investigations tend to show that rate of recovery of the gap is closely associated with the rate of cooling of the gas which has been heated by the passage of the spark, and that residual ionization in the gas is a less important factor, Craggs (4).



Charging Curves for Various Types of Modulators

(a)



Four Electrode Triggered Gap

(b)

Fig. 3

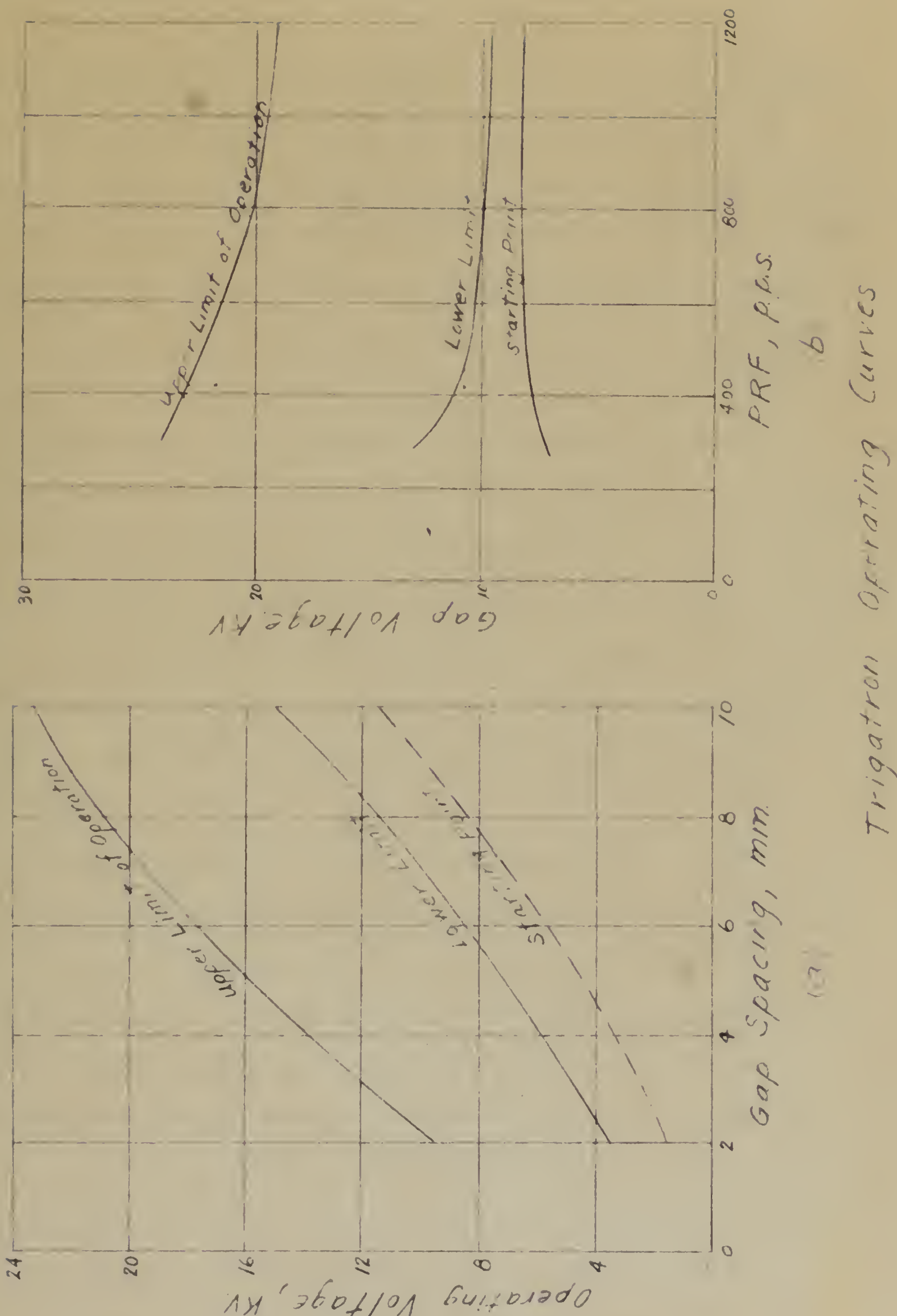
C. The four electrode triggered air gap

Following the work of Craggs (4), Haine, and Meek, in the development of a three electrode triggered gap in which the trigger electrode (surrounded by the common electrode) had its tip in a position of high electrostatic stress due to the main field, Wilkinson(5) developed a modification of this, wherein the essential need for pre-irradiation of the cathode should be effected by illumination from an auxiliary spark, and ventilation by air blown at low pressure. Figure 3(b) shows the general arrangement of the gaps used. Trigger voltage was not applied until a spark had passed from the "starter" to the trigger electrode. This starter-spark was so positioned that it could irradiate, through the trigger annulus, that part of the main electrode (in this case the cathode) which was nearest to the trigger and from which the trigger streamer must be initiated.

Jitter which in the absence of the starter-spark varied between 0.1 and 0.5 microsecond, was reduced by the starter to less than 0.05 microseconds. The reduction in jitter was greatest at the upper limit of the main-voltage range.

d. Experimental results

The curves of figure 4 (a) show some results obtained with a trigatron of the type illustrated in figure 2 (a)



Trigatron Operating Curves
Gap Spacing, mm
Operating Voltage, KV
Gap Voltage KV
PRF, p.p.s.
Lower Limit
Starting Point
b

Fig. 4

when discharging a line capacitance of 0.005 microfarads and pulse duration of 1.2 microseconds into a 125 ohm load at 400 p.p.s. The trigatron operates satisfactorily at any voltage within the limits bounded by the two curves corresponding to the upper and lower operating voltages.

Many electrode materials were tested by Craggs (4) and colleagues but it was found that only tungsten and molybdenum gave satisfactory results. For reasons of convenience of manufacture and ease of supply, molybdenum was finally chosen for the sparking surfaces of the two main electrodes. Tungsten was used for the trigger wire. The use of these two metals not only increased the life of the gap, over that realized with lower melting point metals, but also the characteristics of the gap were improved.

With increasing PRF the operating range of the trigatron decreases as shown in figure 4 (b), which refers to a 0.005 microfarad line discharging into a 125 ohm resistive load. A considerable improvement in the performance of the trigatron, for higher pulse energies at increased PRF's, is obtained by the use of an air blast entering the gap through the trigger hole. The open air trigatron may then be used to switch 2 megawatt, 1 microsecond pulses at a PRF of 1000 p.p.s. Wilkinson (5), as well as subsequent investigators, found that switching

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very high power pulses required an air blast through the main gap.

Wilkinson (5) reports the development of four electrode triggered air gaps capable of switching 12 KV, 55 ampere, 0.5 microsecond pulses at 1500 p.p.s. when supplied with 6 cu.ft. of air per minute through a nozzle at a pressure of 6 inches of water. The electrodes are made of tungsten and have been run over 2000 hours in the British AS442 modulator (A.A. No. 2 Mk II) with adjustment of its starter-trigger gap, and its trigger position, at intervals of 500 hours.

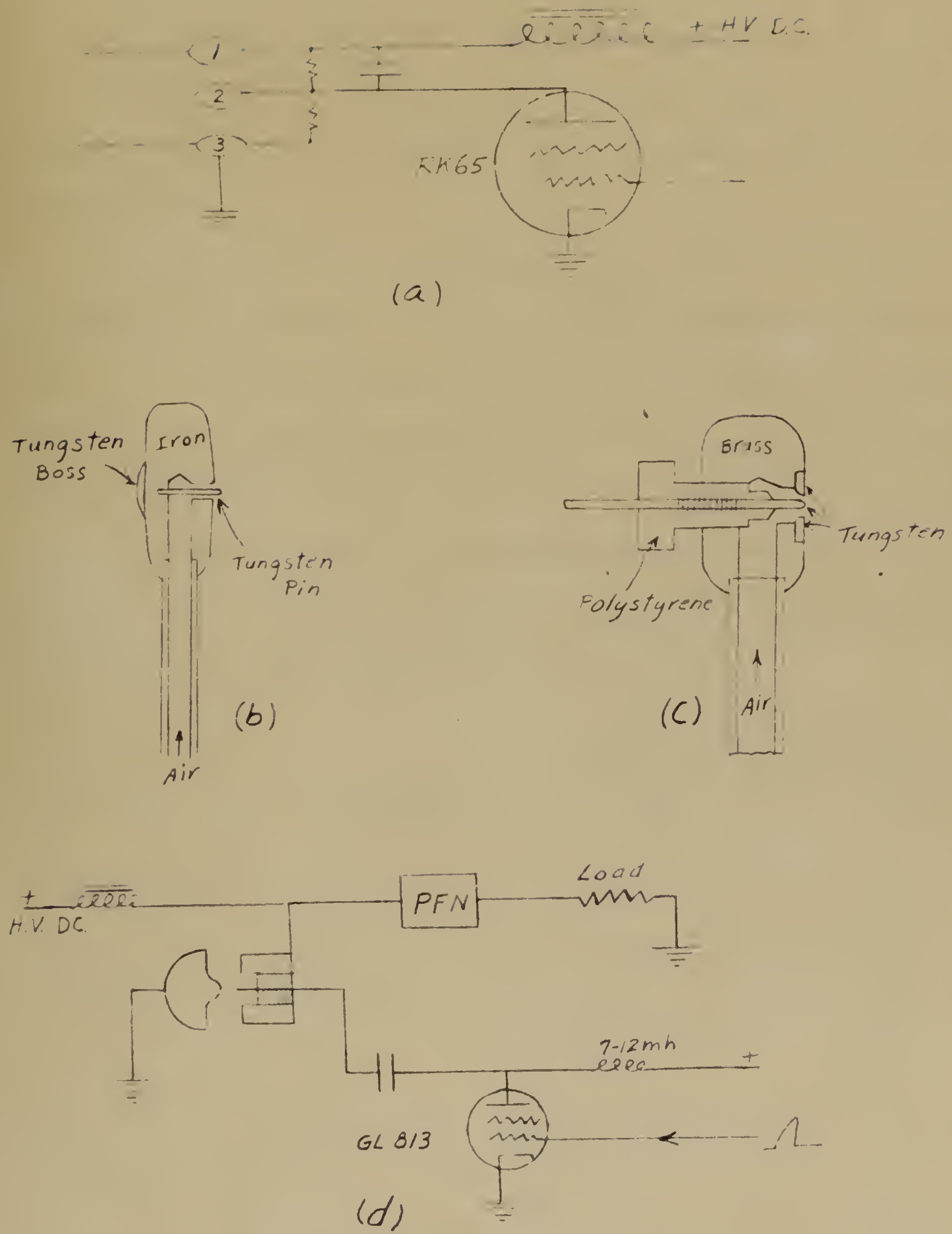
2. General Electric triggered gaps

The early work conducted by Tonks (6) at General Electric was with voltage halving or series type gaps. The gaps consisted of three spheroids, tungsten faced, arranged in a circuit like that shown in figure 5 (a). Tungsten was found to give less wear than other materials tested. (In regard to electrode wear Tonks (6) tested Mo, Pt, Al, Ag, Ta, Carborundum, Brass, Cu, Ni, Zn, Si, Tungsten, and graphite. Of these he found that tungsten was best and molybdenum next best: in general the lower melting point producing the greater wear. He found that wear is a function of pulse length and current). The gaps were triggered by grounding the center spheroid through a tetrode (RK 65). At low voltages it was necessary to

shine ultraviolet light on the cathode surface and also to clear away the ionization of the spaces between spheroids by an air blast. At 2700 p.p.s. a "tremendous quantity of air" was required. It was therefore decided to use air only where the spark jumped. Using the gap shown in figure 5 (b) the arc was confined to a narrow central beam. The tungsten boss on the back of the electrode was the cathode in one gap; the tungsten pin the anode in the other. Polarity was found to be important. Electrode 3, figure 5 (a), carried a boss only; electrode 1 a pin only. The diameter of the tungsten wire was 40 or 60 mil. The spacing between gaps was varied between 1/4" to 5/8". There was found to be a certain limiting ratio between the diameter of the electrodes and the gap length; if the diameter was too small the sparks were erratic. Experimentally the minimum electrode diameter to gap length ratio was found to be 2.5 to 3. The amount of air required depending on the stand-off voltage, pulse rate and current was from 1 to 5 cubic feet per minute.

<u>Spark Trigger Gap</u> (See figure 5 (c))

In later work Tonks (6) modified one spheroid for the voltage halving gap by insulating the axial electrode for spark triggering. The trigger was obtained as shown in figure 5 (d). This gap was run with the trigger electrode flush to the front face of the anode button. Good timing was obtained until the trigger was worn 25 mils in back



General Electric Gaps and Associated Circuits

Fig. 5

of the front face. Greater wear than that caused jitter. Pushing the wire forward restored the gap for normal operation. No ultraviolet light was necessary; or perhaps the trigger itself provided it. It was found that the trigger must have sufficient power to give considerable ionization.

For the spark trigger gap Tonks (6) made a study of minimum and maximum voltage breakdowns over which satisfactory results were obtained, i.e., less than 0.1 microsecond, time jitter. This was done at several pulse repetition rates and with different amounts of air blast. The PFN was 150 ohms giving a 1 microsecond pulse across a load of 150 ohms. Typical results obtained for a gap spacing of 0.35" are shown below in tabular form.

		RANGE OF SAT. OPERATION	
PRF	AIR PRESSURE	MIN.	MAX.
1000 pps	5 #/sp.in.	8.5 KV	13.5 KV
	1.5 "	8.5	12.2
2300	5	7	11.5
	3	7	10.3
	1.5	7	9.5
4600	10	7	10
	5	7	8.6

It is seen that increasing the pulse repetition rate restricted the voltage control range.

Results Obtained by Tonks with Triggered Gaps on Systems

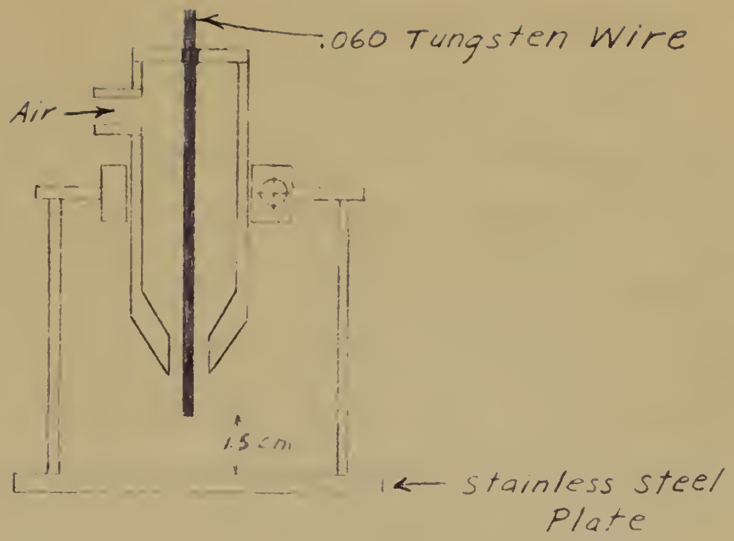
The CXAZ equipment used a triggered spark gap modulator switch producing 15 KV pulses into a 400 ohm load, i.e., about 40 amperes across the gap at a PRF of 656 p.p.s. The gap operated 100 hours with one kickout using a 3/32" orifice. After readjustment of the trigger point it ran 134 hours with two kickouts using a 1/8" orifice. The wear converted to pulse rate was 1/4" of tungsten in 600 hours or 0.014"/day at a PRF of 1000 p.p.s.

The Tonks triggered gap was also tested on the XT-1 equipment which required a 7 KV pulse at 140 amperes. The gap could not handle this power at a PRF of 2000 p.p.s. With a 15 KV pulse, 150 ohm PFN, PRF of 1000 p.p.s., (100 amperes) the gap was run over 240 hours without adjustment. At this point the "timing" sounded bad. The wear on a 60 mil trigger wire was 5.5 mils per day. A total of 17 1/2 days of running wore the tungsten anode button which started with a 91 mil hole to a 97 mil hole, a total of 6 mils. This wear was too much for satisfactory operation.

3. RCA Point-to-plane triggered gap

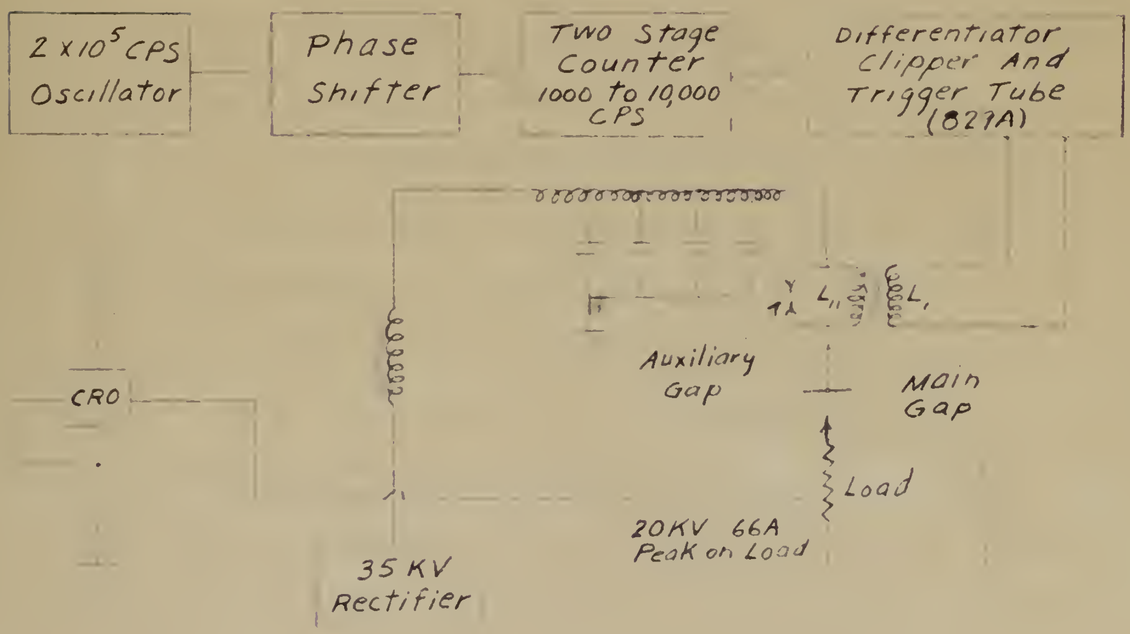
Early in 1942 RCA developed a point-to-plane type of spark gap, the general constructional features of which are shown in figure 6 (a).

It had been found in earlier spark type pulsers that



RCA Point-to-Plane Fixed Triggered Gap

(a)



(b)

Fig. 6

the reverse voltage following the trailing edge of the pulse necessitated the use of a diode across the pulse forming circuit so as to prevent the reverse energy from discharging through the gap. Without the diode the gap was extremely erratic. The gap then used was of a point to point type. In order to obviate the necessity of the damping diode a gap having considerable valve action was developed. This permitted the dissipation of the reversed energy, during the pulse interval without producing reverse current through the gap. To increase the valve action of the gap a coaxial high velocity air stream surrounded the point electrode. This air stream was directed toward the plane electrode as shown in figure 6(a). It was found that about 6 to 14 pounds of air pressure was necessary; below 6 pounds the gap arced. The air stream assured more nearly complete deionizing of the gap with consequent improvement in stability. The air stream served also to limit the temperature rise of the gap electrodes. D. C. tests on this gap indicated a ratio of approximately 2:1 for the non-conducting and conducting directions of voltage. It was observed in these tests that if the point electrode diameter was small with regard to the gap spacing a cold discharge took place about the point electrode and a small "dark current"* existed through the gap. As the voltage was increased the cold

*A subnormal glow discharge which is insufficient to cause an electron avalanche, Windred(2).

discharge gave way abruptly to a continuous discharge. As long as the air pressure was maintained constant and for a fixed electrode spacing, the gap ionizing potential was precise and repeated within an error of plus or minus 2% (i.e., at 30 KV where these tests were performed, the total voltage extreme was 1.2 KV for the resetting inaccuracy.

The circuit arrangement used for overvoltaging of the gap is shown in figure 6(b). An oscillator of the "RC" phase shift type operating at 200 KC supplied a phase shifter permitting phase shifts of nearly 180 degrees. The output of the phase shifter was limited and differentiated to form a pulse suitable for operation of a two stage counter. The output pulse from the final counter was adjusted to a pulse frequency of 1000 cycles per second. This pulse was further differentiated and clipped to provide a positive pulse of approximately 1 microsecond duration for the grid of the trigger tube. This tube was of the modified 829 type. The anode potential of the 829A was 5 KV and the average plate current about 3 ma.

The pulse delivered by the trigger tube was inductively coupled by means of a pulse transformer L_1-L_{11}, figure 6(b), in series with the output terminals of the PFN and the gap. Therefore, the gap was overvoltaged at the trigger repetition frequency. If L_{11} had been allowed to

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[illegible]

[illegible]

remain in the circuit during the pulse the pulse rise time would have been greatly increased. The effect of the inductor L_{11} was therefore removed after the start of ionization of the pulse forming gap by an auxiliary gap shunting the inductor L_{11}. The potential to ionize this gap was derived from the rise of the main pulse and was equal to $L_{11}\frac{di}{dt}$.

Primarily the reason for starting the system at a frequency of 200 KC was to provide, eventually, a means of measuring the time stability of the various stages of the system by superposing the sampled signal on the original sinusoid. The output of the sine wave generator was applied after suitable amplification to a cathode ray oscillograph, and provided a time axis of 2.5 microseconds, five inches in width. Time discrepancies of the sampled energy could therefore be read to better than 0.05 microsecond. The phase shifter enabled the superposing of the sampled pulse on the optimum portion of the originating sinusoid for ease of reading. The modulator was designed to deliver 20 KV pulses, 1 mocrosecond wide, to a 300 ohm load. The peak power output was therefore about 1.3 megawatts. The jitter time was measured as 0.05 microsecond for the leading edge of the pulse and approximately 0.1 microsecond for the trailing edge. The experimental model of this arrangement was operated for approximately 200 hours producing etching of the plane

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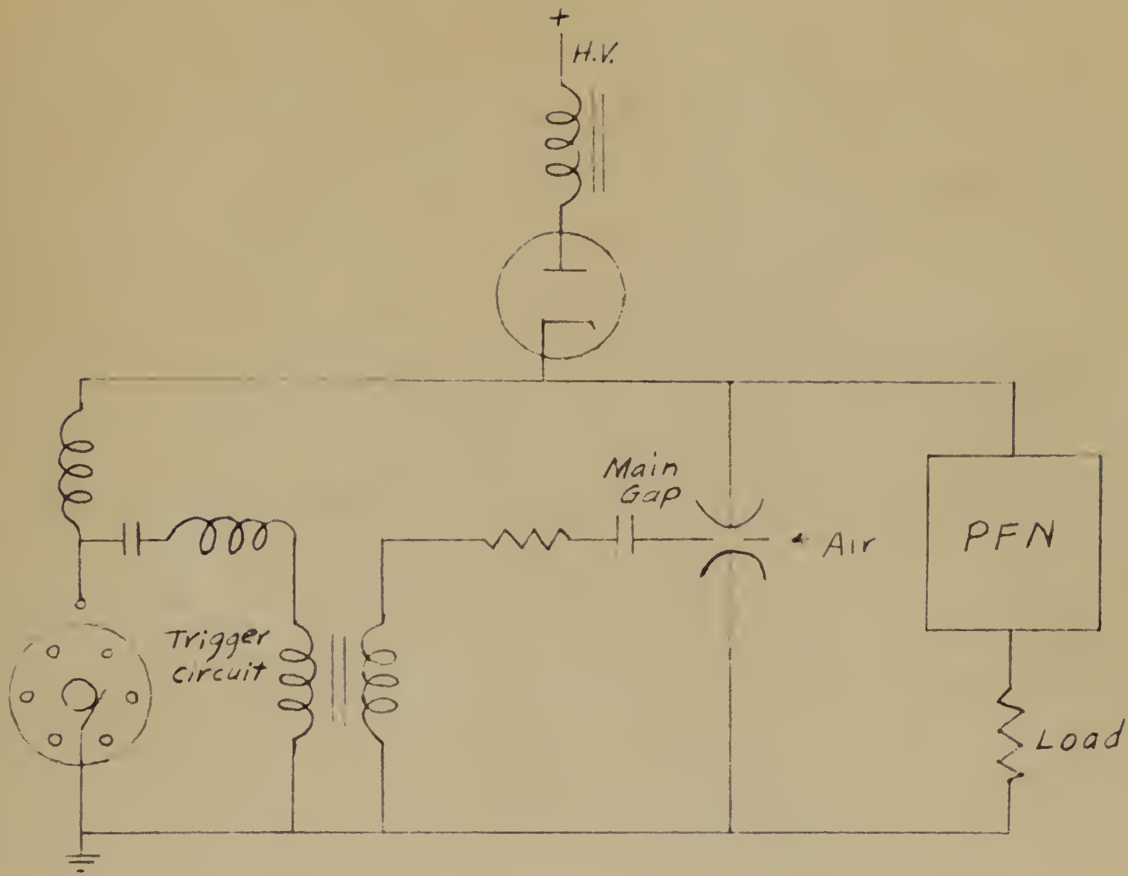
electrode to a depth of approximately 0.002" over an area 1.5 inches in diameter. The point electrode appeared glazed but the amount of metal removed was extremely slight. It was found that the arrangement was not critical to gap adjustment nor air pressure, although dust particles did, on passing through the gap, cause an occasional miss of pulse. A calcium chloride glass wool filter in the air system for filtering and drying effectively removed this form of instability.

Ionization time of the pulse forming gap was measured by superposing increments of the trigger voltage and the main pulse on the 2.5 microsecond time axis. The leading edge of the main pulse lagged the peak of the trigger pulse by 0.15 microsecond and was essentially constant.

4. Bell Laboratories Triggered Gap

In July 1942 Mr. W. M. Goodall of Bell Telephone Laboratories reported an experimental megawatt pulser using a three electrode fixed gap, Goodall (8). The The general circuit arrangement used is shown in figure 7. The control voltage for this triggered spark gap was obtained from a rotary gap and pulse transformer. The pulse rate was 480 pulses per second and the power delivered to the load was about 2 megawatts peak for a 1 microsecond pulse. An air blast was directed through



Bell Laboratories Triggered Gap Circuit

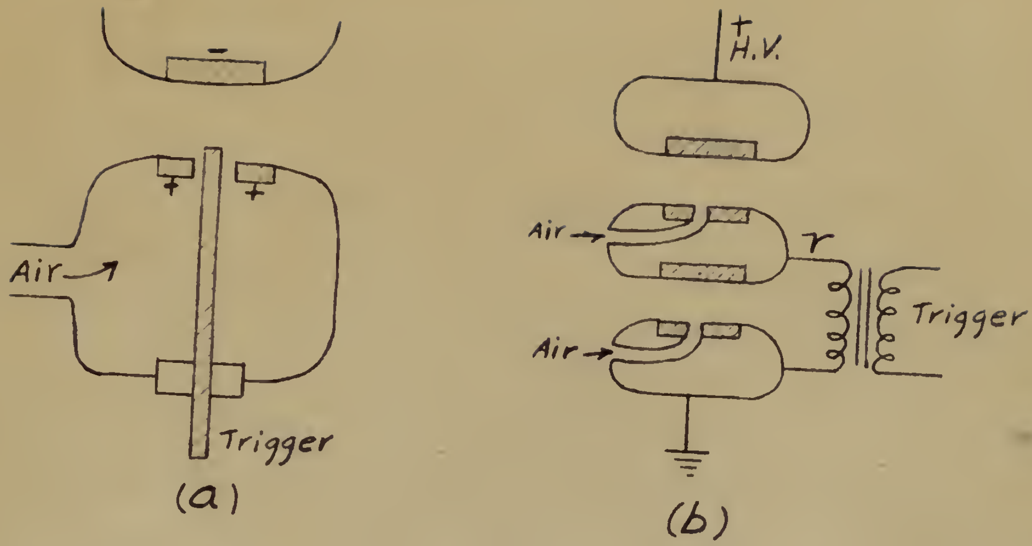
Fig. 7

the gap to clear away the ionized air. The gap was found to need adjustment at intervals of 300 to 400 hours. This adjustment only required the turning of a knob a fraction of a turn. One gap had been run for a total of over 1200 hours at a gap current of 400 amperes. The electrode material used was molybdenum. The unit was designed to operate with 10 KV on the fixed gap (5 KV across the load). The voltage control range was about 25% for a fixed gap setting. It was found that less trouble was encountered in extinguishing the fixed gap if suction was used instead of blowing. With a vacuum cleaner motor as a blowing device 110 volts were required, whereas 60 volts would do the job when the motor was used as a suction device. More effective air flow lines in the latter case are believed to account for the better operation.

No information is available as to the jitter time obtained with this gap. It was undoubtedly of the order of 50 microseconds or greater because of the trigger source used.

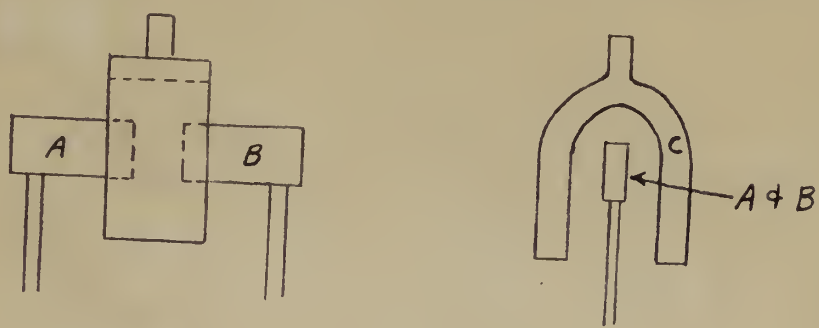
5. Radiation Laboratory Triggered Gaps

Figure 8(a) is a rough sketch of one type of fixed gap which was experimented with at the Radiation Laboratory during the war. The cross-hatched parts were made of tungsten. At 40 amperes and 30 KV this arrangement had an adjustment free life of about 100 hours. No



Radiation Laboratory Triggered Gaps

Fig. 8



Cross Section Views of Veatron

Fig. 9

information is available as to pulse rate used or air blast necessary.

Following work reported by the English on the trigatron the above gap was enclosed in a glass envelope at a pressure of 2 atmospheres of a mixture of 95% Argon and 5% Oxygen. This mixture worked about as well and had a longer life, than one of 90% Argon and 10% Oxygen, then being used by the English. The life of the former was of the order of 200 hours.

Another gap configuration tried at the Radiation Laboratory is shown in figure 8(b). No data is available regarding the results obtained with this gap, which was very similar to one used by Tonks (see figure 5(a). Soon after work started on the hydrogen thyratron and the English trigatron the Radiation Laboratory apparently stopped work on triggered air gaps.

6. Westinghouse Triggered Gaps

The early work at Westinghouse Electric Corporation on fixed spark gaps centered mainly on Ignitrons, Veatrons and Trigatrons, Slack (10) & (14).

Ignitrons were developed which were capable of switching 50 KV pulses at 1000 p.p.s., passing currents of 100 amperes at an ambient temperature of 40 degrees C. The best life obtained was about 100 hours; failure of the ignitor being the source of trouble. Ignitrons have the disadvantage of requiring an erect stable mounting

and work on these tubes was stopped early in 1942.

The Veatron* is a vacuum arc switch the general arrangement of which is shown in figure 9. It consists of a very narrow gap between two electrodes A and B and a third electrode which is U-shaped. A and B are the trigger electrodes, an arc being started between them by field emission. Either A or B is the cathode, and C is the anode. The trigger arc transfers to the anode if C is positive and greater than 150 volts. The spacing between A.and B must be maintained at about 1 to 3 mils for satisfactory operation. Voltages up to 40 KV can be switched with this device and its handles currents of several hundred amperes. The Veatron was seriously limited by wearing away of the trigger electrodes and, although a mechanical device was developed for keeping the gap spacing within the working range, it never came into general use.

Beginning in May 1942 Westinghouse concentrated on enclosed pressure gaps similar to the British trigatron, Slack(10). The possibility of improving the British design was investigated. In addition Slack considered radically different designs using various combinations of gases at high pressures in an attempt to get a design to operate at around 25 KV, switching pulses of better than 1 megawatt. Considerable work was done on trigger pin height, pin spacing and main gap

*Westinghouse Electric Corp. designation.

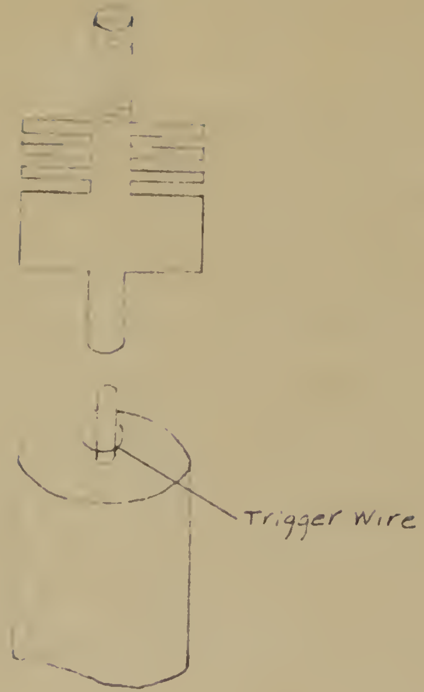
spacing. In general with a small pin spacing of the order of 30 to 40 mils between the pin and the outer cup, the range of operation was independent of pin height. Larger pin spacings would operate at lower pressures. It was found however that for the higher PRF's a closer main gap spacing and high pressures were needed.

7. Camp Evans Signal Laboratory Modulator

This triggered spark gap modulator was reported at the Modulator Colloquim, Radiation Laboratory in June 1943, Gorhan(11). It attempted to eliminate the wear on the triggering electrode found in most triggered spark gaps. This wear is caused by the fact that the fine triggering electrode is often part of the main spark discharge.

This modulator boasted that at pulse repetition rates of 200 to 400 pulses per second, no air blast, cooling, nor ultra violet light was required for accurate synchronization. (Note: A source of ultra violet light is sometimes used as the trigger to provide ions to iniate the arc.)

Essentially the gap (figure 10) consisted of a 1/4" cathode, a 3/32" anode, and a triggering electrode extending around about 120 degrees of a 3/16" radius arc. An electrostatic plate about 3/4" in diameter was located about 1/4" below the main gap and 1/8" below the triggering electrode. The triggering electrode



Evans Signal Laboratory
Triggered Gap

Fig. 10

was made of 10 or 15 mil tantalum and had a sharp inner edge. The main gap separation was roughly 1/4" and voltages of 10 to 15 KV were controlled.

The triggering voltage was generated by an R-C oscillator feeding a blocking oscillator which cut off an 807 tube having about 30 mh. as a plate load. The pulse output voltage of this circuit was roughly 200 volts and was sufficient to control voltages up to at least 15 kilovolts.

This gap was run for 1000 hours at 200 cycles per second with about 20% tolerance in operation voltage and 1/20 of a microsecond jitter. There was no visible corona or spark between the triggering electrode and the main electrode, so that the wear on the triggering electrode was imperceptible. The triggering electrode was located far enough below the main gap so that small changes in electrode lengths, due to wear, did not appreciably change the firing requirement. Wear was compensated for by means of screw adjustment of the anode.

Since all the parts were stationary and the main electrodes were made of inert metals, this was enclosed in a double wall celotex box so as to reduce the sound of the gap.

The life test on this gap was run with a 50 ohm resistive load to represent the load presented by the

primary of a pulse transformer delivering one megawatt, 1 1/2 microsecond pulses to a transmitting tube.

III

CURRENT WORK ELSEWHERE

1. University of California High Power Gaps

a. General Nature of Work

During the last 2 years the Microwave Laboratory of the University of California has been investigating triggered spark gaps as a possible switch for high power resonatrons, Marshall(12)&(13). In their experiments they have charged pulse lines to various voltages in the range up to 70 KV and switching has been accomplished with various types of triggered spark gap circuits. These triggered spark gap circuits were found to give excellent performance and reliability in switching peak powers of 200 to 400 megawatts, at average powers of 50 to 80 kilowatts, and it appears that these powers can be exceeded. Triggered spark gap circuits were developed which have a very low jitter time, of the order of 0.01 microsecond, which permit a very rapid voltage rise across the load and which have a large voltage control range, 2 to 1 or greater.

Tests were conducted to determine the optimum size of trigger gap and trigger electrode. In their early experiments small gaps and trigger electrodes were used. These were operated for approximately 250 hours in a circuit with the following characteristics:

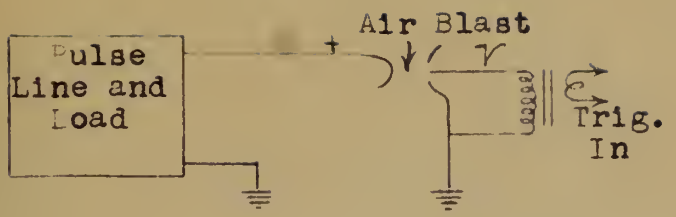
Stand-off Voltage	Up to 65 KV (operated most of the time at approx. 50 KV)
Pulse Length	280 microseconds
PRF	7.5 p.p.s.
Pulse Line Z_o	50 ohms (i.e., usual peak power approx. 12.5 megawatts)
Main Electrodes	2 3/4" diameter copper with 2" R face
Trigger Wire	0.016" diameter copper wire
Trigger Hole	0.036" in diameter
Gap spacing	1.3 inches
Air pressure for Blowing Gap	Approx. 3 pounds
Jitter Time	Approx. 0.1 microsecond

The erosion of the electrodes was not excessive; the 0.016" trigger wire still was essentially flush with the ground electrode surface. The edges of the 0.036" trigger hole was worn down a little and the untriggered electrode was eroded down to somewhat of a flat over a region 3/4" in diameter.

In their more recent work with extremely high power pulses Professor Marshall (12) and colleagues have directed their efforts toward closer study of high voltage trigger gap operation. Reasons for changing to high trigger voltage were:

(1) Large trigger gap dimensions are impervious to erosion changes.

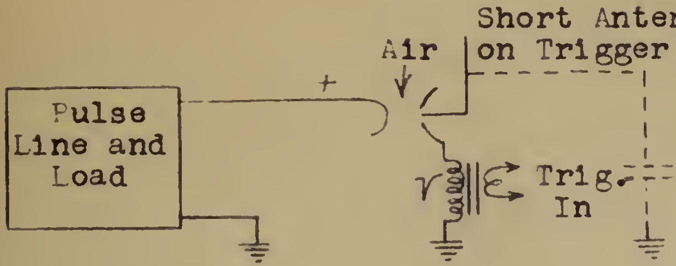
(2) More triggering action permits increased voltage control range.



Advantages: Simplicity
Fast rise time

Disadvantages:
Limited voltage control range

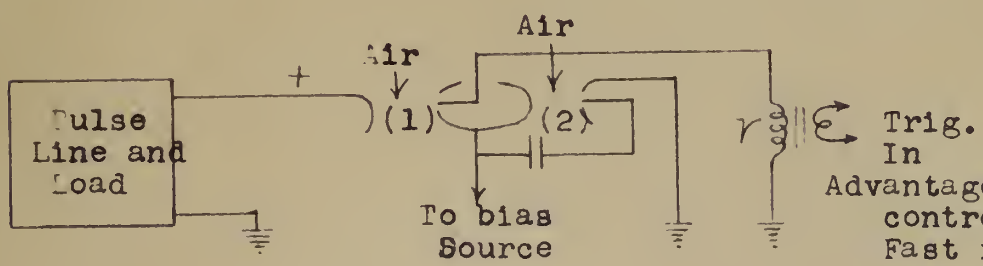
(a) Simple Triggered Gap with no Overvoltage



Advantages: Wide control range with high dependability

Disadvantages: Slow pulse rise time because of added impedance of pulse transformer

(b) Overvoltaged Triggered Gap



Advantages: Wide control range
Fast rise time

Disadvantages:
Complicated Circuit

(c) Two Overvoltaged Triggered Gaps

TYPICAL TRIGGERED SPARK GAP CIRCUITS

Fig. 11

PERFORMANCE OF SIMPLE TRIGGERED GAP USING LARGE ELECTRODES WITH 3/8" TRIGGER ROD IN 1" HOLE

Figures indicate jitter time in hundredths of a microsecond as estimated by observation of a model P-5 synchroscope; first figure is average jitter, second figure is maximum jitter (excluding unsynchronized pulses).

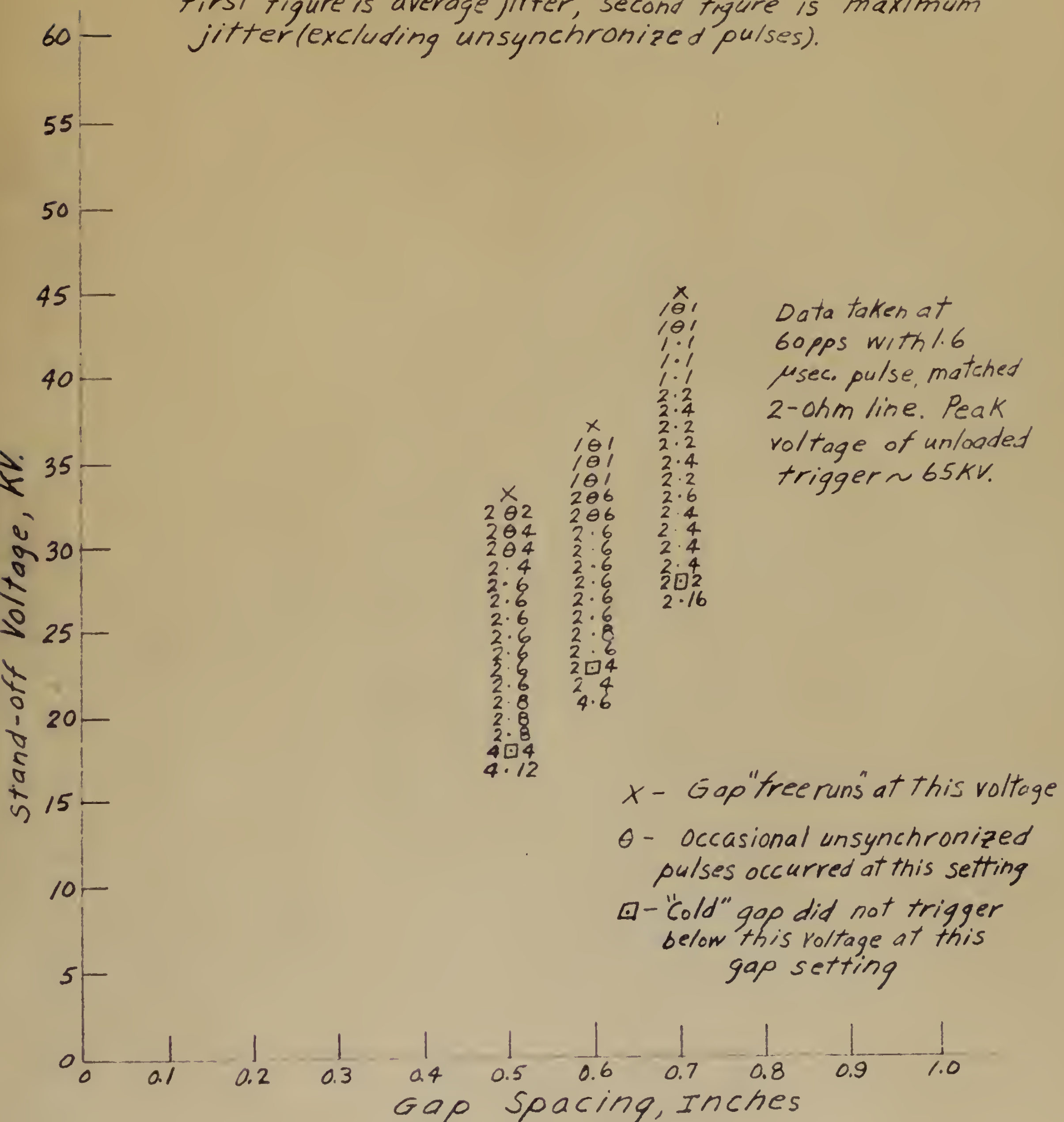


Fig. 12

PERFORMANCE OF SIMPLE TRIGGERED GAP USING LARGE ELECTRODES WITH 5/8" TRIGGER ROD IN 1" HOLE

Figures indicate jitter time in hundredths of a microsecond as estimated by observation of a model P-5 synchroscope; first figure is average jitter, second figure is maximum jitter (excluding unsynchronized pulses).

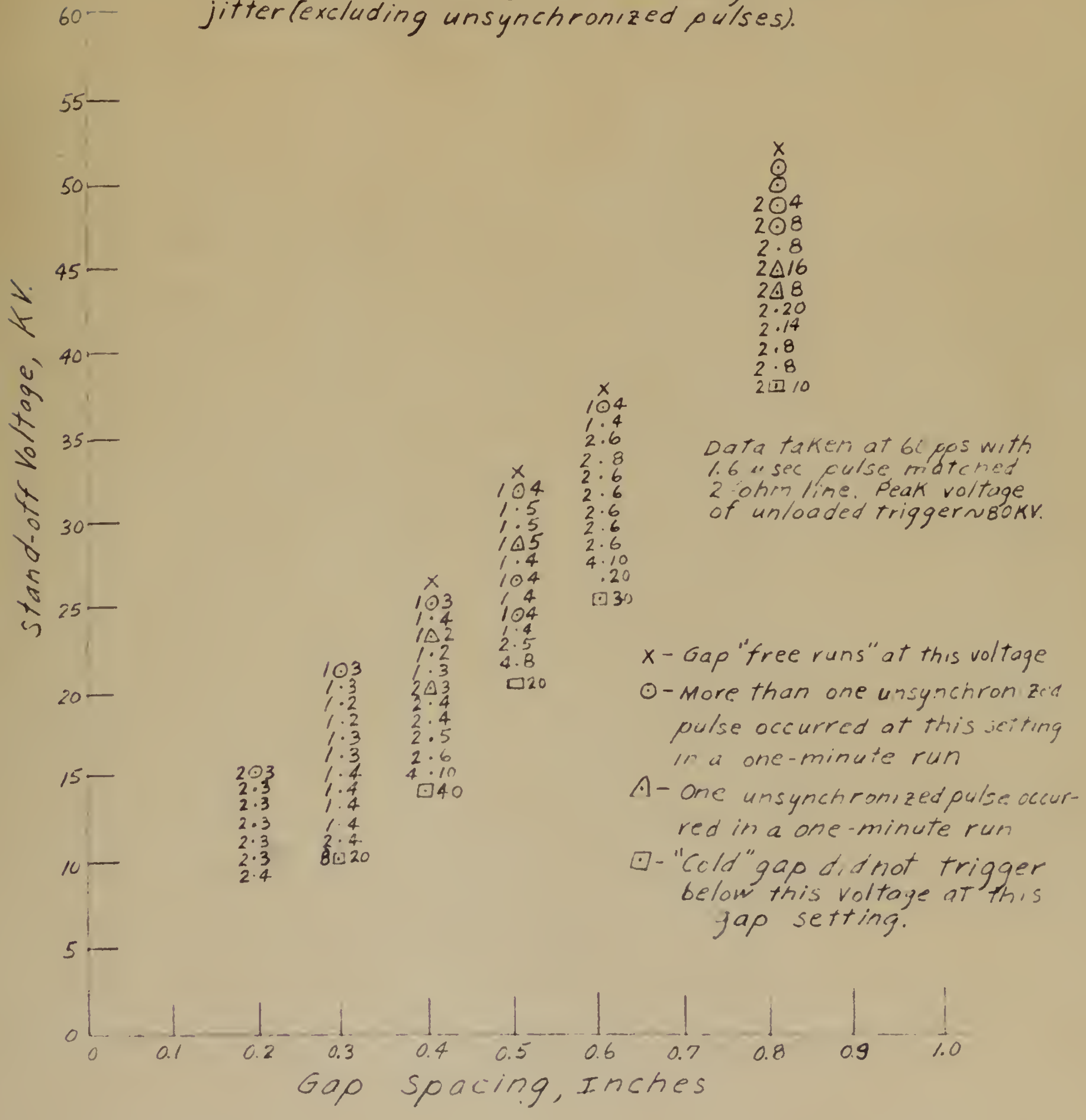


Fig. 13

(3) Greatly reduced jitter time.

The main electrodes being used in these latter experiments are elliptical in shape and about 9" in diameter. The trigger electrodes are 3/8" or 5/8" rods centered in a a 1" hole in the ground electrode.

Some typical spark gap circuits used are shown in figure 11.

b. Simple triggered gap with no overvoltage

The simple triggered gap shown in figure 11 (a) is one in which firing is brought on solely by the presence of triggering spark. The gap setting can be adjusted for any voltage setting, e.g., 50 kilovolts. Voltage control range is approximately 25% for a fixed gap setting, e.g., 37.5 KV to 50 KV. The simple triggered gap permits fast voltage rise time across the load because of the low impedance circuit. Using large trigger gaps and high voltage trigger (i.e., trigger voltage rises toward 70 KV) jitter time is less than 0.01 microsecond near the free-running gap voltage.

Some typical data for operation of simple triggered gap with no overvoltage are shown in figures 12 and 13.

C. Overvoltaged triggered gap

The control range of the triggered gap can be extended considerable if the gap is overvoltaged and triggered by means of a pulse transformer in series with the gap and the load, as shown in figure 11 (b). This circuit is also cap-

able of very high voltage, very high power, relatively jitter free operation, with a very large voltage control range. However, the pulse line must discharge through the secondary of the overvoltaging and triggering transformer, thereby increasing the voltage rise time across the load. The circuit is excellent if long pulses are used and the slow rise time is not objectionable.

In applications where short pulses and or fast rise times are desired it is impossible to insert the secondary of the pulse transformer in series with the gap and still maintain a fast rise of the main pulse. A triggering pulse transformer with a core which is easily saturated by the main pulse tends to overcome this difficulty, but various drawbacks are encountered, particularly with high pulse current and power.

Tests made at the University of California Radiation Laboratory, with short pulse lengths, demonstrated the feasibility of using a hydrogen-filled discharge tube to short out the secondary of the triggering pulse transformer after it had provided the trigger and overvoltage to breakdown the air gap. It was found that even when an r.f. glow was maintained in the gas discharge tube to minimize jitter time, the tube presents a high enough impedance to the triggering pulse for a fraction of a microsecond to allow the triggering pulse transformer to properly overvoltage and trigger the air gap. The hydrogen discharge tube has been

recently eliminated by substituting a second triggered spark gap to short cut the secondary of the overvoltaging and triggering transformer after the breakdown of the first gap.

d. Two Overvoltaged Trigger Gaps

The most satisfactory triggering circuit was found to be that shown in figure 11 (c). In this circuit the polarity of the trigger is opposite to that of the high voltage gap electrode, so that the first gap is overvoltaged by the trigger after the small triggered gap has been broken down. In the meantime the second small triggered gap fires and thus gap number 2 is prepared to breakdown quickly once it receives the full pulse line voltage as a result of breakdown of gap number 1.

During tests made at the University of California on this type circuit jitter times of 0.05 microseconds or less were obtained over an operating range of approximately 50% of the maximum voltage for the gap setting. More than 15,000 amperes at a repetition rate of 30 pulses per second, 5 microseconds wide, were handled with this gap at a standoff voltage of approximately 58 KV. This corresponds to 435 megawatts peak power switched, and an average power of 65 kilowatts. At somewhat reduced voltages the tests were performed at repetition rates of 60 pulses per second. For handling high currents, the use of tungsten trigger points was found to be advisable in order to minimize deterioration.

About June 1950 the Microwave Laboratory, University of California, plans to issue a technical report covering their work on triggered spark gaps and giving information from which a triggered gap may be designed to meet a particular need.

2. Air Force Research Laboratory High Power Gap

Currently the Air Force Cambridge Research Laboratory, Cambridge, Massachusetts, is working with triggered open-air spark gaps with the object of gaining information for the design of a suitable switch for a 200 megawatt modulator. The factors of chief interest in this connection are reliable operation and long life. As of March 1950, a relatively small amount of work had been accomplished and no reports had been written on the subject. The first tests were conducted with 2 inch diameter spheres of chromium plated brass. The grounded electrode contained a hole approximately 1/8" in diameter, in the center of which was located a 1/16" diameter tungsten trigger electrode. This gap configuration was found to give good operation over a range of charging voltages from the maximum operable value down to 70 per cent of this value, for one setting of the gap spacing. Time jitter varied inversely with forward anode voltage from several microseconds at low voltage to approximately 0.1 microsecond at the maximum operable voltage, for one setting of the gap spacing.

Some life tests have been conducted under the following conditions:

Stand-off Voltage	60 KV
Pulse Current	2670 Amperes
Pulse Power	80 Megawatts
Pulse Length	1.23 Microseconds
PRF	60 p.p.s.

The chromium plate disappeared immediately from the sparking area. Operation continued satisfactorily for about one hour at the end of which time the gap began to fire prematurely. Examination of the sparking area under a microscope showed the formation of ridges and globules on the anode ball, with one globule much larger than the rest. The large globule protruded 0.011 inches from the surface of the sphere and was responsible for the premature breakdown of the gap. Removal of this protrusion permitted normal operation again for about one-half hour, at the end of which time another globule had formed. This process was repeated a number of times, always with similar results. The copper in the sphere had probably melted during the arc and been drawn into globules which apparently consisted of crystalline copper metal coated with black copper oxide. The cathode ball showed no such formations, but the copper was worn away from it more rapidly than from the anode ball.

A tungsten rod 1/4" in diameter was then inserted into the anode ball and smoothed off flush with the surface

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A tungsten rod 1/4" in diameter was then inserted into the anode ball and smoothed off flush with the surface

of the ball to serve as a sparking area. This operated 18 hours with no trouble and very little wear on the tungsten. Failure was caused by sparking to the adjacent brass which caused the formation of a globule and the familiar premature firing. Recently a pair of 6 inch diameter brass electrodes, with round tungsten inserts 3 inches in diameter which form the sparking areas, have been built. These new electrodes will be tested in the near future.

IV

CURRENT WORK AT WESTINGHOUSE

1. The experimental modulator

The current work undertaken at Westinghouse Electric Corporation was for the purpose of investigating the possibility of using an open air triggered spark gap switch in a high-power high repetition rate modulator. The general design specifications for this modulator are:

Power Output of Magnetron	2 Megawatts
Load Impedance R_o	20 Ohms
PRF and Pulse Length	1200 p.p.s.- 1 microsecond
	300 p.p.s.- 4 microseconds

Assuming 40 per cent magnetron efficiency the power input to the magnetron must therefore be

$$2 \text{ megawatts} \times \frac{100}{40} = 5 \text{ megawatts.}$$

Assuming 5 per cent losses in the pulse transformer the power input required to the load is

$$5 \text{ megawatts} \times \frac{100}{95} = 5.26 \text{ megawatts.}$$

The peak pulse voltage across the load will then be

$$E = \sqrt{\text{power out} \times R_o}$$

$$E = \sqrt{5.26 \times 10^6 \times 20}$$

$$E = 10.25 \text{ KV}$$

Assuming 5 per cent loses in the charging reactor and PFN and a 600 volt drop across the charging diode the D.C. voltage needed is

$$10.25 \text{ KV} \times \frac{100}{95} \quad 600 = 11.4 \text{ KV D.C.}$$

In order to have a working range it was decided to use 13 KV D.C. supply voltage and to charge the PFN to nearly twice this value (say 25 KV) using D.C. resonance charging with a hold-off diode. The general layout of the modulator is shown in figure 14. In the absence of the output pulse transformer and magnetron a 20 ohm water-cooled load, made up of non-inductive Ward Leonard plaque resistors, was used. A single choke was decided upon for the final charging reactor in order to eliminate the necessity of changing charging chokes when changing PRF. The charging inductance therefore had to be small enough to permit the PFN to charge up to full voltage each time, at the highest PRF.

The schematic diagram of the PFN used is shown in figure 15. A single section was used for the 1 microsecond pulse giving a pulse shape of a half cycle of a sine wave which is half critically damped. Since 4 sections were used for the 4 microsecond pulse, the pulse shape was more nearly rectangular. The choice of R_0, the characteristic resistance of the PFN, and , the pulse length, dictates the values of storage capacitance, C_{st}:

[illegible]

[illegible]

[illegible]

[illegible]

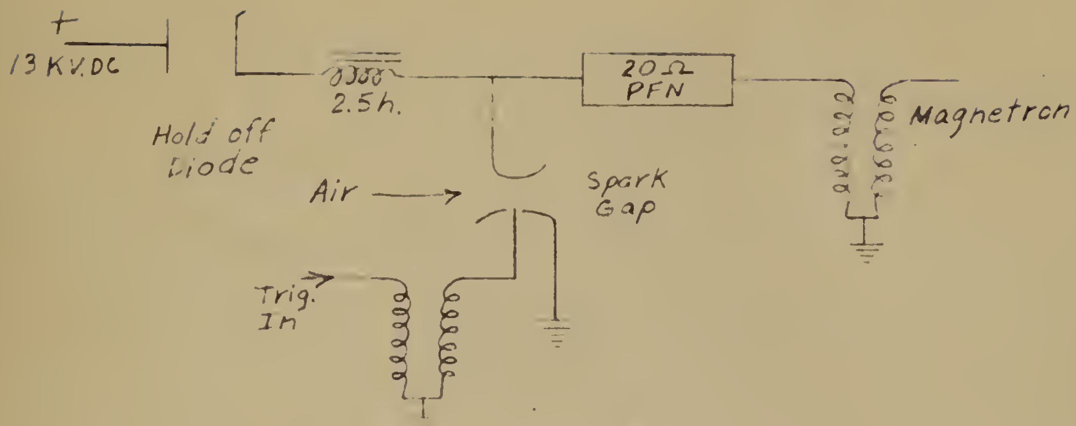
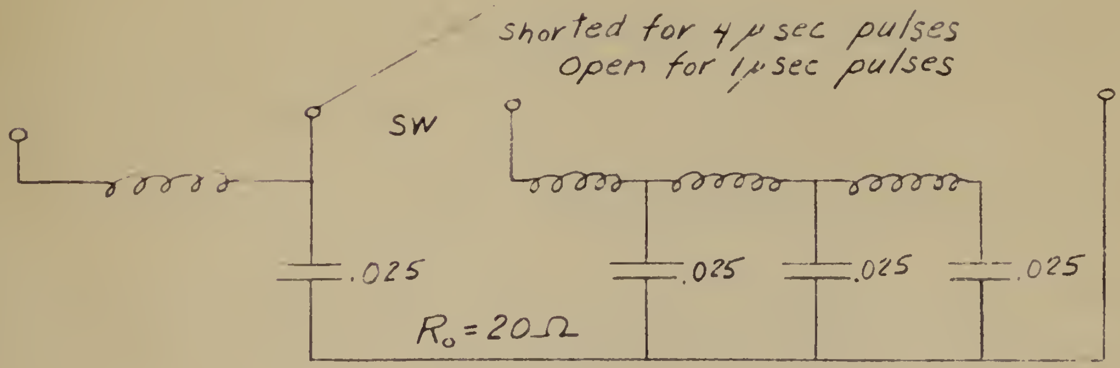


Fig. 14



PFN Schematic

Fig. 15

$$\delta = 2 R_o C_{st} \text{ , Glasoe (3)}$$

For the 1 microsecond pulse,

$$C_{st} = \frac{\delta}{2R_o} = \frac{1 \times 10^{-6}}{40} = 0.025 \text{ microfarad.}$$

For the 4 microsecond pulse,

$$C_{st} = \frac{4 \times 10^{-6}}{40} = 0.1 \text{ microfarad.}$$

When the spark gap fires the load current is

$$I_L = \frac{12.5 \text{ KV}}{20 \text{ ohms}} = 625 \text{ amperes.}$$

Peak power output of modulator is

$$P = \frac{E^2}{R_L} = \frac{(25)^2}{20} = 7.8 \text{ megawatts.}$$

Average power input to modulator at 1200 p.p.s.

$$= 7.8 \times 10^6 \times 1200 \times 1 \times 10^{-6} = 9360 \text{ watts}$$

Average D. C. current required

$$= \frac{9360}{13\text{KV}} = 0.72 \text{ amperes D.C. (at 1200 PRF)}$$

To realize a PRF of 1200 with C_{st} = 0.025 microfarad, using D.C. resonant charging, the charging choke must resonate with C_{st} at a frequency of 1200/2 = 600 cycles or greater.

$$L = \frac{1}{\omega^2 C_{st}} = \frac{1}{(2\pi \times 600)^2 \times .025 \times 10^{-6}} = 2.82 \text{ henries}$$

To allow for tolerance in construction of the charging choke and the PFN, the charging choke was designed to have an inductance of 2.5 henries, giving a charging circuit resonant frequency of 638 cycles/sec. At 1200 p.p.s.

$$I_c \text{ peak} = \frac{E}{\omega L} = \frac{13 \text{ KV}}{2\pi \times 638 \times 2.5 \times 10^{-6}} = 1.3 \text{ amperes.}$$

For the 4 microsecond pulse length the PRF = 300 and the resonant frequency of the charging circuit resulting is

$$f = \frac{1}{2\pi\sqrt{2.5 \times 0.1 \times 10^{-6}}} = 318 \text{ c.p.s.}$$

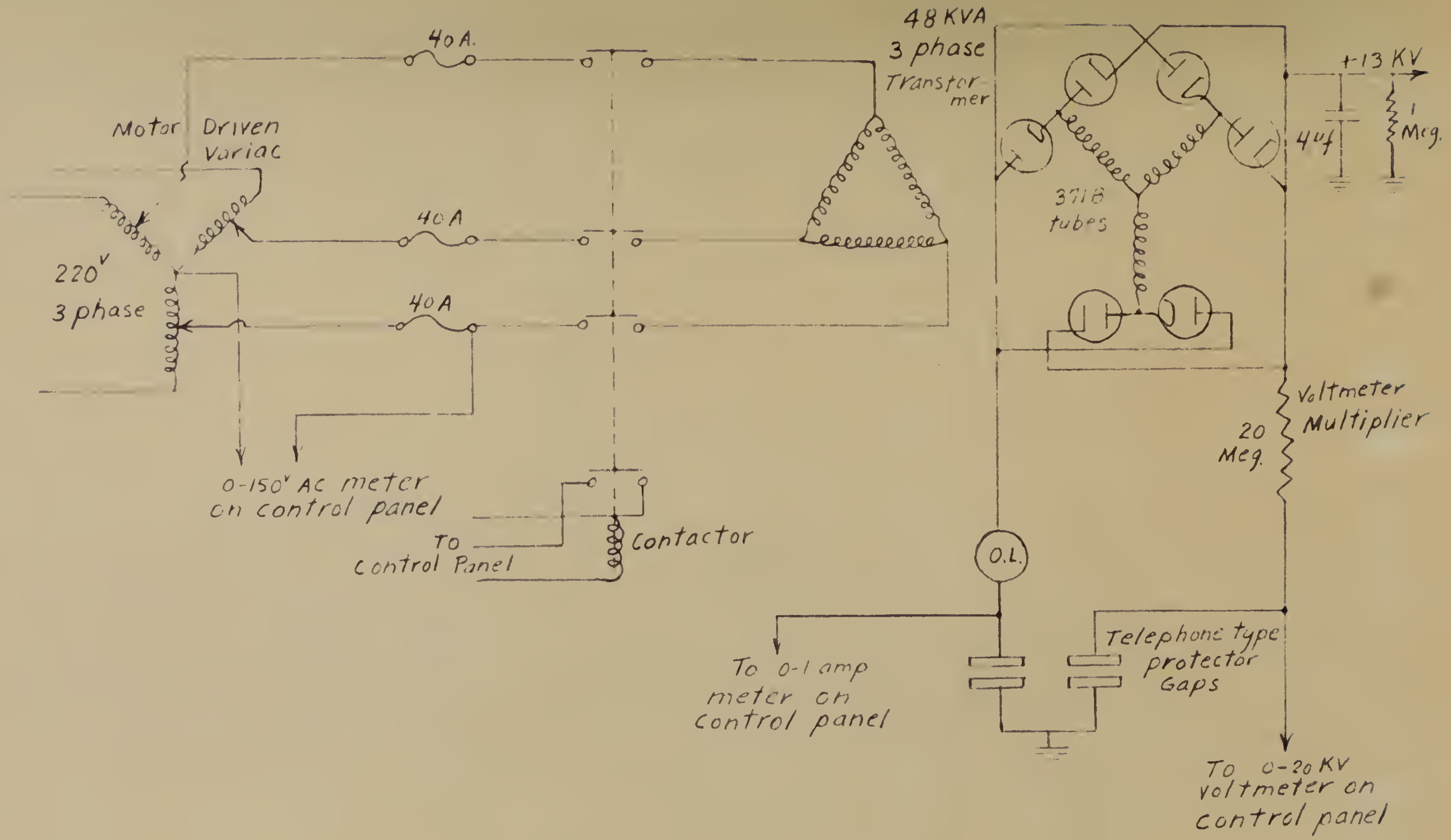
At 300 p.p.s.

$$I_c \text{ peak} = \frac{13 \text{ KV}}{2\pi \times 318 \times 2.5 \times 10^{-6}} = 2.6 \text{ amperes.}$$

A UE 576 was chosen for the hold-off diode.

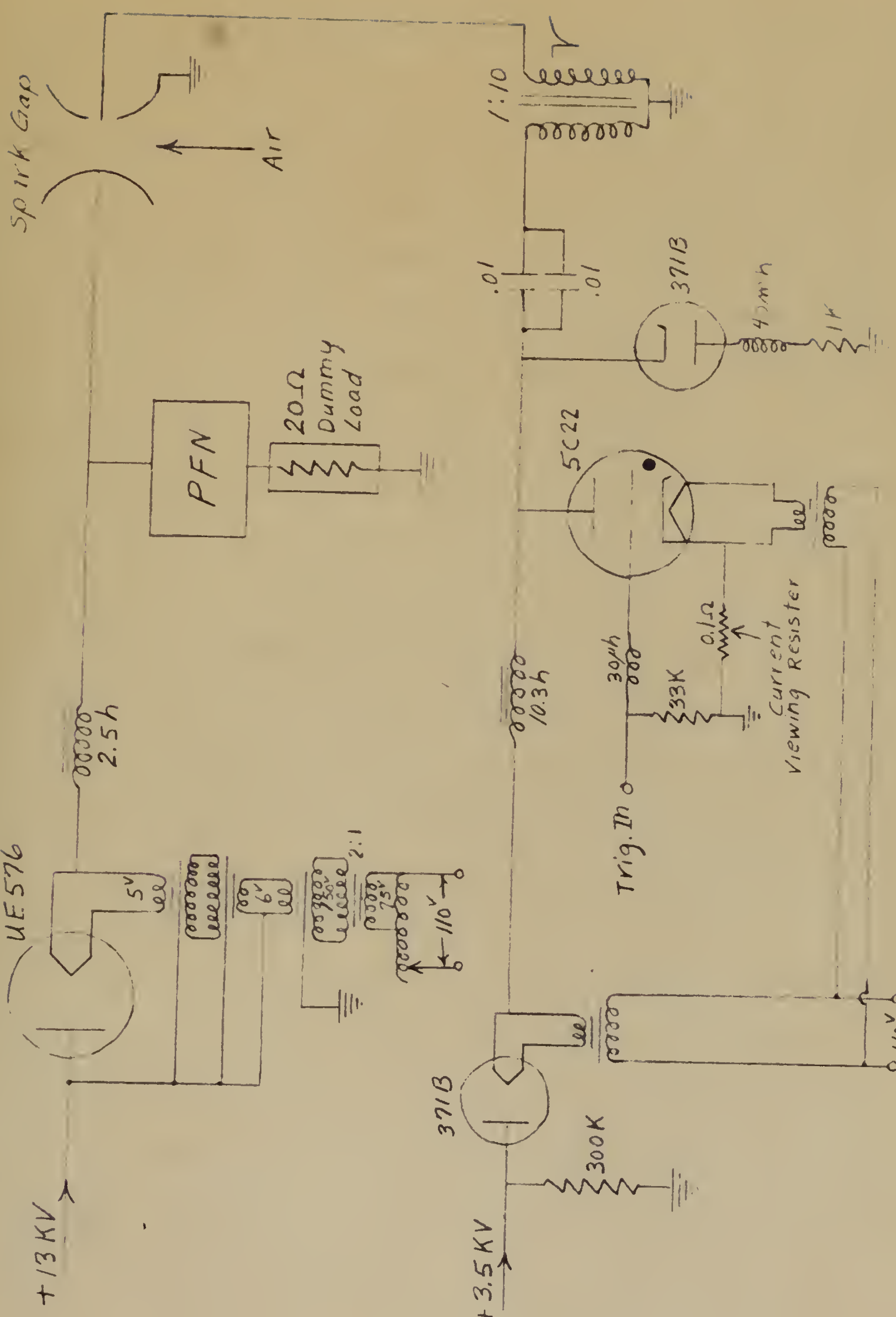
For the main high voltage power supply a 48 KVA, 3 phase, induction heater transformer was used. This transformer delivers 11 KV D.C. at 4 amperes with 210 volts into its primary windings. By raising the primary voltage an output voltage of 15 KV D.C. was obtained at reduced current. The schematic of the main high voltage supply is shown in figure 16. Six 371B rectifier tubes were used giving full wave rectification. A 4 microfarad filter capacitor was used with a 1 megohm bleeder resistance.

The schematic diagram of the experimental modulator is shown in figure 17. A complicated filament supply was



Main Power Supply

Fig. 16



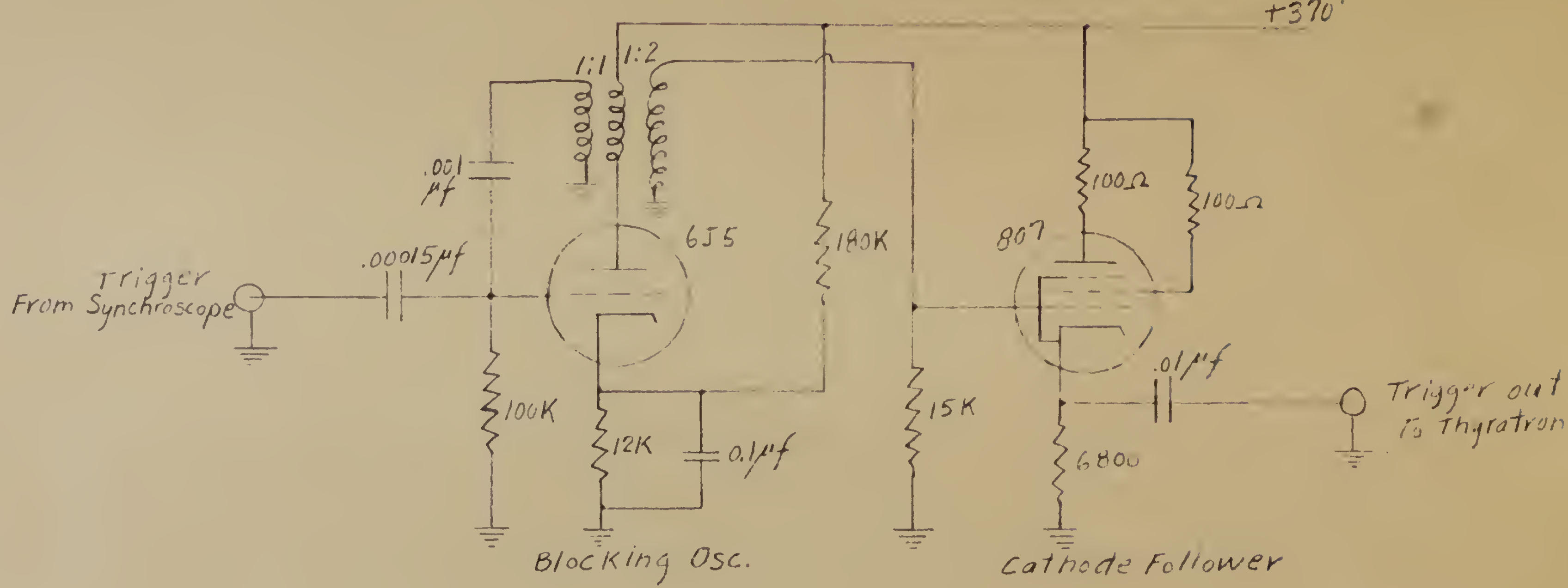
Modulator Schematic

Fig. 17

necessary for the hold-off diode. The only filament transformers readily available were insulated for 13 KV, so it was necessary to place two of them in series with another low voltage rating filament transformer between them in order to insulate the cathode of the hold-off diode for the 26 KV peak voltage. This dropped the filament voltage to about 4 volts and made necessary the use of an additional step-up transformer and variac.

The trigger supply was designed to give an open circuit voltage of 70 KV across the trigger gap. This high trigger voltage was desired to give a very short rise time, thereby reducing the pulse jitter time. D. C. resonant charging with a diode was used to charge a 0.02 microfarad capacitor to 7 KV. At the proper instant this capacitor was discharged through the primary of a 1:10 step-up pulse transformer by a 5C22 hudrogen thyratron. A large laboratory power supply rated at 0-20 KV D.C. and 0-100 ma was used to supply the trigger power. A damping diode was used across the 5C22 to remove the inverse voltage left on the 0.02 microfarad capacitor after each pulse. A resistor and inductor in series with this diode were found necessary to reduce the peak current through the diode to acceptable values.

The trigger for the hydrogen thyratron was obtained from a synchroscope which was keyed by an audio oscillator.



Trigger Amplifier Schematic

Fig. 18

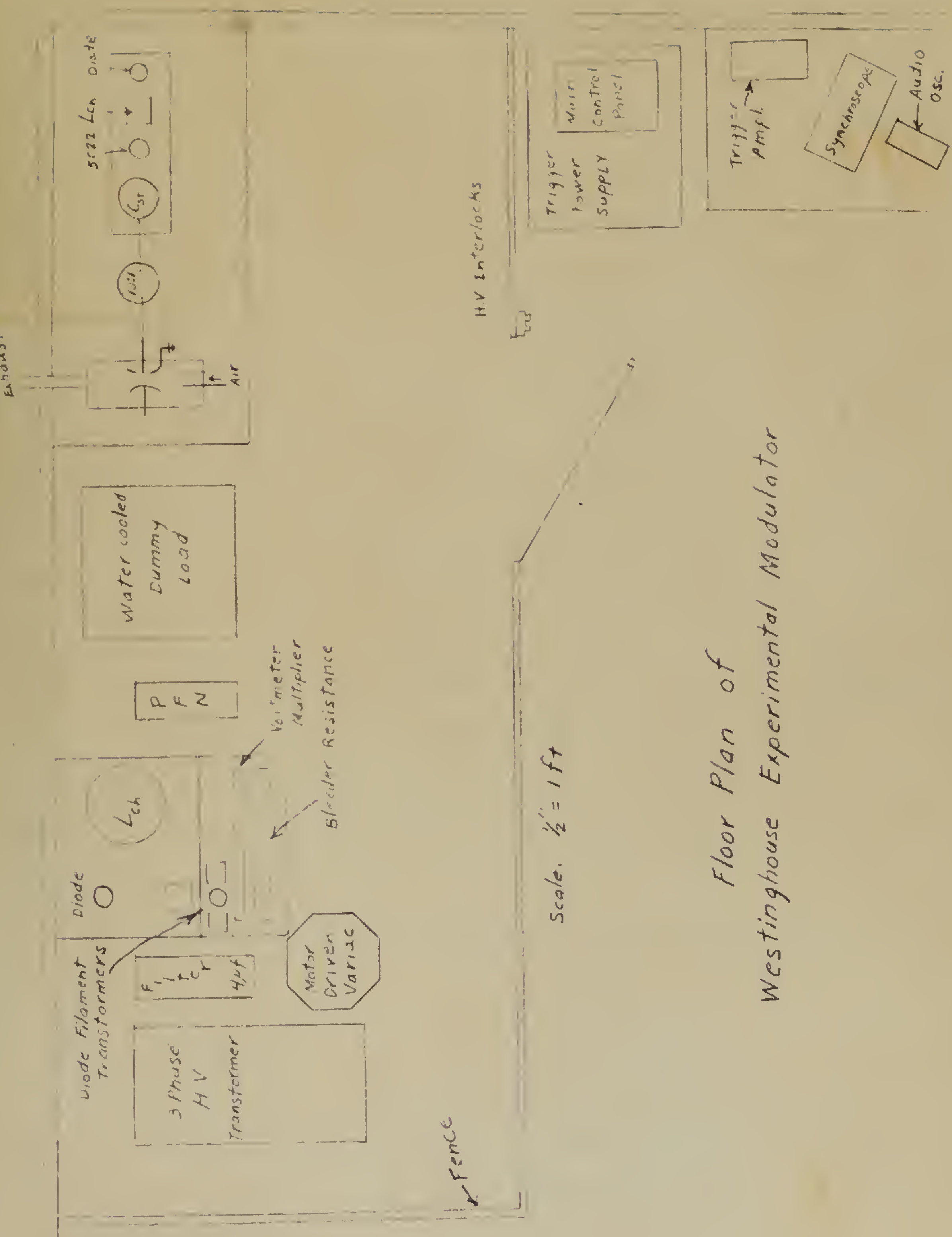

Exhaust
5C22
Lch
Diode
Air
H.V Interlocks
Trigger Power Supply
Main Control Panel
Trigger Ampl.
Synchroscope
Audio Osc.
Water cooled Dummy Load
PFN
Voltmeter Multiplier
Bleeder Resistance
Lch
Diode
Diode Filament Transformers
Filter
4μf
Motor Driven Variac
3 Phase HV Transformer
Fence
Scale. ½" = 1 ft
Floor Plan of
Westinghouse Experimental Modulator

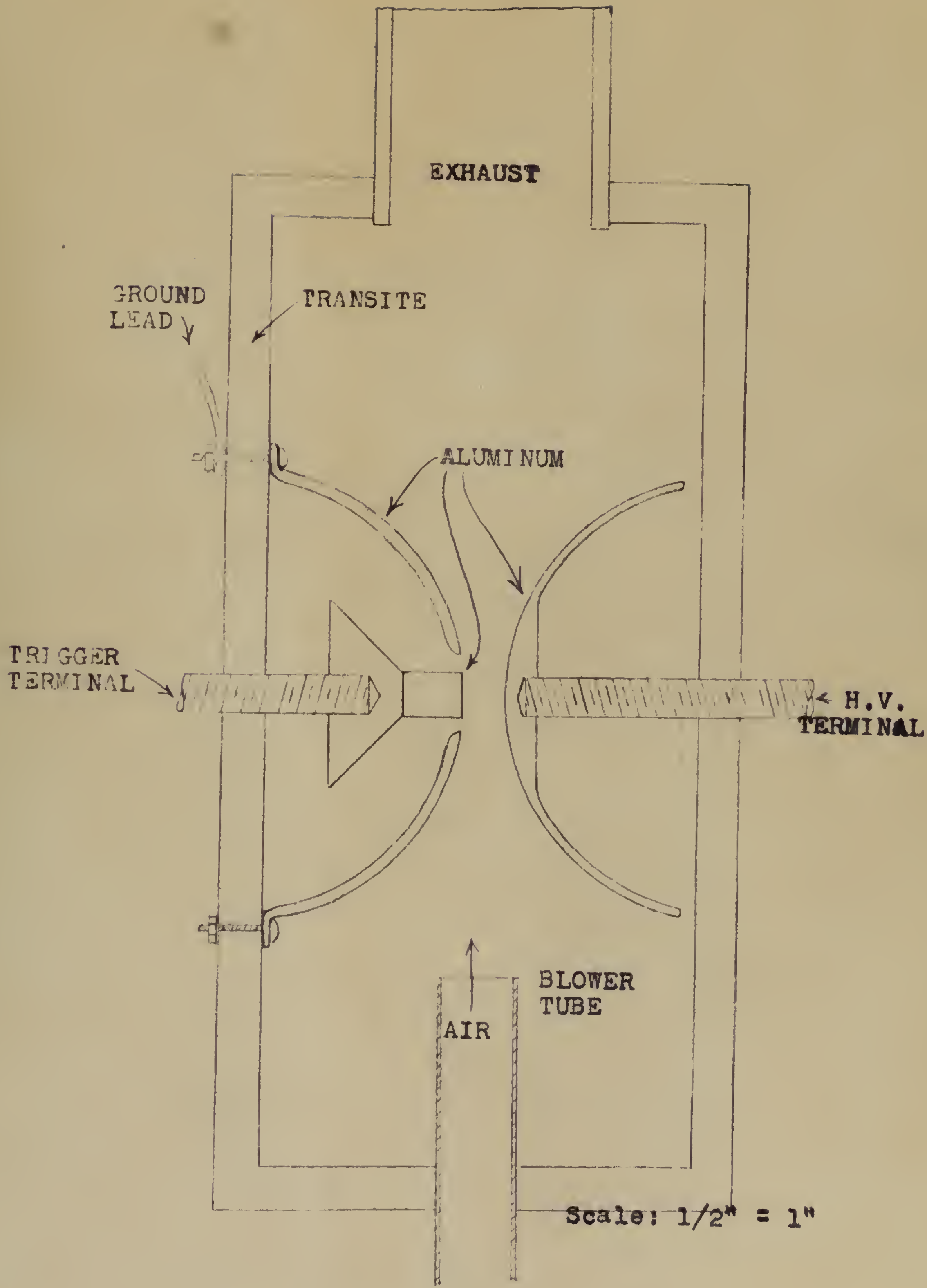
Fig. 19

This arrangement was used to simplify construction and to permit ease of viewing circuit waveforms. Since the trigger output of the sunchroscope was rather weak for triggering the hydrogen thratron, a trigger amplifier was used. The schematic diagram of the trigger amplifier is shown in figure 18. It consists of a blocking oscillator and and 807 cathode follower. The 6J5 blocking oscillator is maintained below cutoff in the absence of a triggering voltage. It was designed to work over the range of 300 to 1200 cycles/sec. The .00015 microfarad coupling capacitor between the synchroscope and the blocking oscillator grid was necessary to prevent the relatively wide synchroscope pulse from double triggering the blocking oscillator. A despiking circuit consisting of the coupling cable capacity (about 250 micromicrofarad) and a shunt inductance of 30 microhenries was used to prevent grid spikes from the thyratron from reacting back into the blocking oscillator.

The floor plan of the experimental modulator is shown in figure 19.

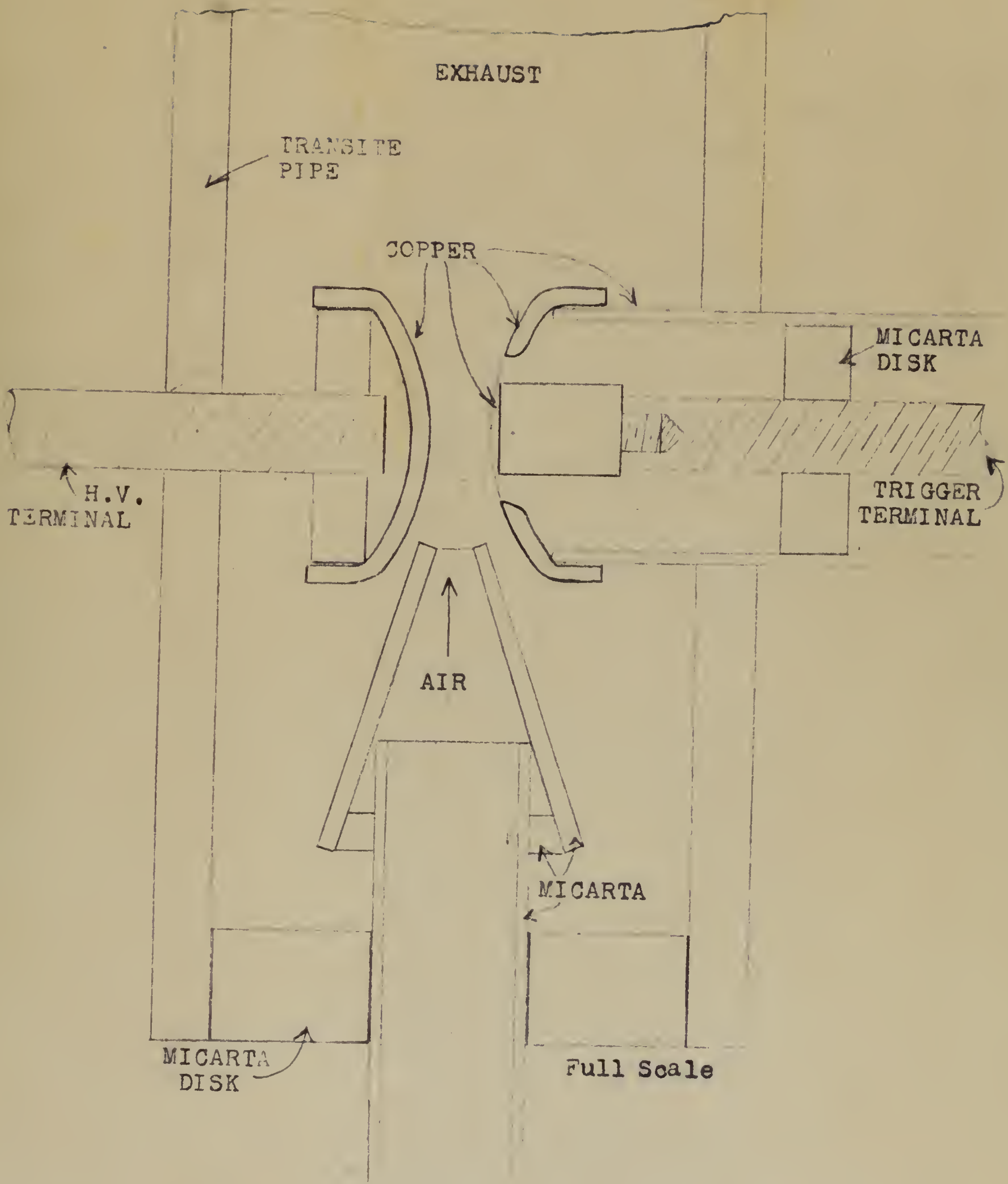
2. Electrode design

A sketch of the first gap tested in the above modulator is shown in figure 20. This gap followed closely a design suggested by Prof. L. C. Marshall (12) and (13) of the University of California for switching 20 megawatt pulses at 60 p.p.s. with a standoff voltage of 40 KV.



Cross Section View of Westinghouse
Gap No. 1 and Housing

Fig. 20



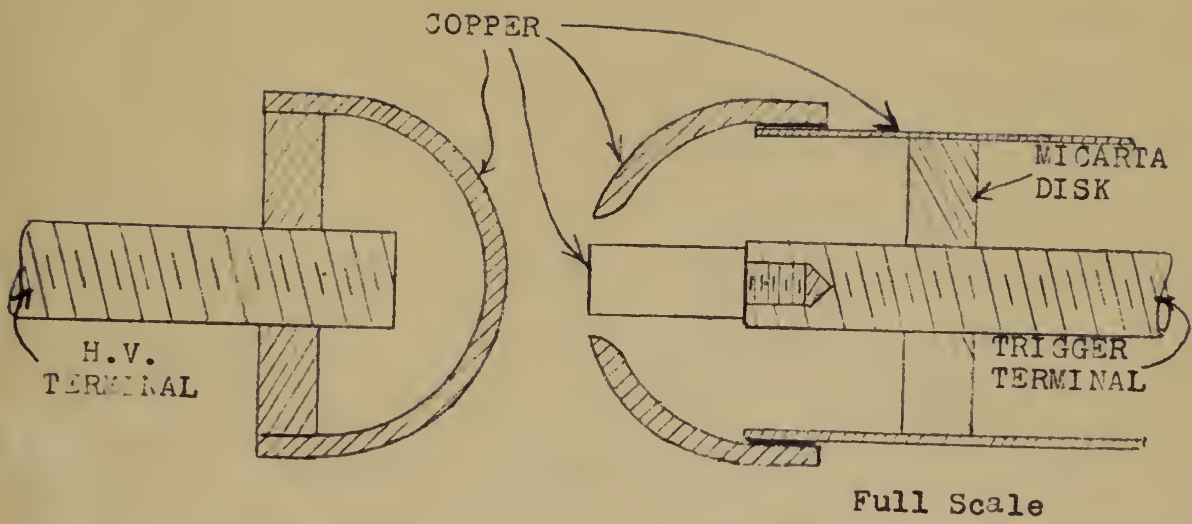
Cross Section View of Westinghouse
Gap No. 2 and Housing

Fig. 21

The main electrodes were hemispheres 5 1/2" in diameter. A 5/8" trigger electrode was used in a 1" hole in the ground electrode. It was soon learned that the electrodes were much larger than necessary for the lower pulse powers to be switched, since the electrodes ran cool and the arc was concentrated in a very small central area of the electrodes. It was also observed that when the gap "free ran"* the arc took place across the wide part of the gap near the exhaust end. This took place at powers and PRF's much lower than the design specifications called for. These first electrodes were made of aluminum and eroded quite rapidly. The high voltage electrode had a central area about 3/4" in diameter which was pitted badly after a relatively few hours of operation.

The electrodes shown in figure 21 were designed to reduce gap size and thereby permit better scavenging of the ionized air with a reduced air supply. The main electrodes were 1 7/8" in diameter; the faces having a 1 1/2" radius of curvature in an attempt to spread the arc over a wider area of the electrodes. The trigger electrode was 3/8" in diameter centered in a 5/8" hole in the ground electrode. Copper was used as the electrode material in gap number 2 because of ease of manufacture, however, although the erosion was much less than with the aluminum, it was readily apparent that copper would permit only

* Gap self ignites before triggered.



Cross Section View of Westinghouse
Gap No. 3

Fig. 22

a relatively short life. For lack of a better housing at hand the gap was mounted in a transite pipe having an inside diameter of 3 inches. This arrangement looked promising at first since 8 megawatts were switched at a PRF of 150 p.p.s. It was found, however, that upon being heated the transite pipe ceased being a good insulator, and arcing took place between the high voltage electrode and the pipe. The electrodes were then mounted in the large rectangular box shown in figure 20. Results obtained with this arrangement were slightly better than with the large electrodes.

The latest gap tested at Westinghouse is shown in figure 22. These copper electrodes are similar to those of figure 21 except that they are hemispheres 1 7/8" in diameter. It was felt that the sharp corners on the previous gap electrodes contributed to erratic firing. Using these hemispheres and a large amount of air (see section 3 below) the design specification of switching 8 megawatts at 1200 p.p.s. may be met.

3. Air blast problems

The success realized by previous experimenters in the field, notably Marshall (12) at the University of California, using a vacuum cleaner blower to provide the air blast for the gap, led to trial of this method in the beginning. This blower was capable of supplying about 50 cu.ft. of air per minute through a 1" diameter blower tube, giving a velocity through the gap of around 5000

[illegible]

ft./min. At 1200 p.p.s. this means that the ionized air will travel only about 0.7" before the full standoff voltage has again been applied to the gap. The large rectangular box (figure 20) used with the original gap gave poor air flow characteristics and effectively reduced the interpulse air travel distance.

In the second gap (figure 21) a nozzle 1" by 1/4" was used to concentrate the air blast in the center of the gap. Since the vacuum cleaner blower operates poorly against a back pressure, a 1/4" compressed air line was used for the air supply. Complete tests were impossible with this gap because of the failure of the housing. It was apparent however that the better gap scavenging obtained because of the improved air flow lines permitted operation at higher pulse powers and high repetition rates.

With the most recent gap tested the nozzle outlet has been reduced to 1/4" by 1/2" and the air supply line increased to 3/4" in diameter. The line pressure of 100 lbs./sq. in. is reduced at the nozzle input to 7.5 lbs/sq.in. and about 200 cu.ft. of air per minute is blown through the gap. In order to effectively reduce the gap housing a 3" diameter micarta tubing has been cut to slide over the electrodes. The air nozzle is centrally located just at the edge of the electrodes and extends slightly inside the micarta exhaust tubing. With this arrangement, borderline operation has been obtained at peak pulse powers of 8 megawatts switched at a PRF of 1200 p.p.s.

At various times during the tests air was supplied through the trigger gap with and without a main gap air blast. No noticeable improvement in operation was obtained by ventilation of the trigger gap.

In order to improve gap air flow characteristics it is believed that a next step will be to extend the main electrodes surfaces along the air flow path using insulator material. The purpose of this is to prevent expansion of the air and therefore maintain a high air velocity until the air is well past the conducting electrodes. At present the air supply necessary makes the triggered spark gap an impractical switch for combinations of high powers and high repetition frequencies.

V

CONCLUSIONS

During World War II triggered open air spark gaps were used by the British, and to a lesser extent in the United States, as radar modulator switches at high pulse repetition rates and low powers.

Recent work shows that future applications of triggered open air spark gaps will probably be in very high power (i.e., hundreds of megawatts) modulators operating at relatively low repetition rates, of the order of 250 p.p.s. or below. The author believes that in this operating range the triggered open air spark gap is better in cost, reliability, and power handling capability, than other modulator switches presently available.

Open air triggered spark gaps are very useful as laboratory switching devices since, by the simple expedient of changing the gap length, a given gap can operate at any power below its rating. Seasoning of magnetrons can therefore be accomplished easily using this type of modulator switch.

While the recent tests at Westinghouse are inconclusive, they tend to show that triggered open air spark gaps are impractical for combinations of very high powers and high repetition rates.

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